**CHAPTER 3. MARKET AND TECHNOLOGY ASSESSMENT**

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# CHAPTER 3. MARKET AND TECHNOLOGY ASSESSMENT

## 3.1 INTRODUCTION

This chapter details the market and technology assessment that the U.S. Department of Energy (DOE) has conducted in support of the ongoing energy conservation standards and test procedures rulemakings for general service fluorescent lamps (GSFL) and incandescent reflector lamps (IRL). These rulemakings are mandated by the Energy Policy and Conservation Act (EPCA), as amended, and are effective for lamps manufactured during and after July, 14, 2012.

This chapter consists of three sections: the market assessment, the technology assessment, and product classes. The market assessment provides an overall picture of the market for the products concerned, including the nature of the products, industry structure, and manufacturer market shares; regulatory and non-regulatory efficiency improvement programs; and market trends and quantities of products sold. The technology assessment identifies a list of technologies to consider in the screening analysis. The product classes section discusses the product classes DOE considered using for this rulemaking and how they were developed.

The information DOE gathers from the market and technology assessment serves as resource material for use throughout the rulemaking. DOE considers both quantitative and qualitative information from publicly available sources and stakeholders in this assessment.

### 3.1.1 Definitions

This rulemaking covers certain types of fluorescent and incandescent reflector lamps. Section 321(30) of EPCA (42 U.S.C. 6291(30)) contains definitions for “fluorescent lamp,” “general service fluorescent lamp,” “incandescent lamps,” and “incandescent reflector lamp.” DOE codified in the CFR the statutory definitions and definitions of supplementary terms for fluorescent and incandescent lamps. 62 FR 29222 (May 29, 1997); 10 CFR section 430.2. Appendix 3A lists these terms and their definitions.

As part of this energy conservation standards rulemaking, DOE is considering extending coverage to additional GSFL. (42 U.S.C. 6295(i)(5)) The following sections describe in more detail EPCA’s definitions for fluorescent and incandescent lamps, note DOE’s interpretation of the definitions, and note the definitions DOE is considering revising or developing. Please see section III of the final rule Federal Register notice associated with this rulemaking for more discussion on DOE’s consideration of additional fluorescent lamps, its interpretation of EPCA’s definitions and its consideration revise non-statutory definitions.

#### 3.1.1.1 Fluorescent Lamps

Section 321(30)(A) of EPCA (42 U.S.C. 6291(30)(A)) defines a fluorescent lamp as:

“a low pressure mercury electric-discharge source in which a fluorescing coating transforms some of the ultraviolet energy generated by the mercury discharge into light, including only the following:

(i) Any straight-shaped lamp (commonly referred to as 4-foot medium bi-pin lamps) with medium bi-pin bases of nominal overall length of 48 inches and rated wattage of 28 or more.

(ii) Any U-shaped lamp (commonly referred to as 2-foot U-shaped lamps) with medium bi-pin bases of nominal overall length between 22 and 25 inches and rated wattage of 28 or more.

(iii) Any rapid start lamp (commonly referred to as 8-foot high output lamps) with recessed double contact bases of nominal overall length of 96 inches and 0.800 nominal amperes, as defined in ANSI C78.1-1978 and related supplements.

(iv) Any instant start lamp (commonly referred to as 8-foot slimline lamps) with single pin bases of nominal overall length of 96 inches and rated wattage of 52 or more, as defined in ANSI C78.3-1978 (R1984) and related supplement ANSI C78.3a-1985."

In a final rule published May 29, 1997, DOE updated section 321(30)(A)(iv) references of American National Standards Institute (ANSI) standards by changing "ANSI C78.3-1978" and "ANSI C78.3a-1985" to ANSI C78.1-1991 and C78.3-1991.[a] 62 FR 29222.

#### 3.1.1.2 General Service Fluorescent Lamps

Section 321(30)(B) of EPCA (42 U.S.C. 6291(30)(B)) defines general service fluorescent lamps as:

"fluorescent lamps which can be used to satisfy the majority of fluorescent applications, but does not include any lamp designed and marketed for the following nongeneral lighting applications:

(i) Fluorescent lamps designed to promote plant growth.

(ii) Fluorescent lamps specifically designed for cold temperature installations.

(iii) Colored fluorescent lamps.

(iv) Impact-resistant fluorescent lamps.

(v) Reflectorized or aperture lamps.

(vi) Fluorescent lamps designed for use in reprographic equipment.

[a] ANSI C78.3-1978 is an ANSI-published guide to standard characteristics for instant start and cold-cathode fluorescent lamps. C78.1-1978 is the equivalent guide for rapid start fluorescent lamps. Supplements to C78.3-1978 and C78.1-1978 update the guides over time. In 1991, ANSI combined the original standards with their supplements into C78.3-1991 and C78.1-1991, respectively. In 1997, DOE incorporated definitions for fluorescent lamps into the Code of Federal Regulations (CFR). 62 FR 29238. DOE used the statutory definition, but replaced "ANSI C78.1-1978 and related supplements" with "ANSI C78.1-1991" and replaced "ANSI C78.3-1978 (R1984) and related supplement C78.3a-1985" with "C78.3-1991."

(vii) Lamps primarily designed to produce radiation in the ultra-violet region of the spectrum.

(viii) Lamps with a color rendering index of 87 or greater."[b]

As part of this rulemaking, under the authority of 42 U.S.C. 6295(i)(5), DOE has considered extending coverage to additional general service fluorescent lamps. In the final rule Federal Register notice, DOE considers extending energy conservation standards coverage to the following list of "additional general service fluorescent lamps":

- 4-foot, medium bipin (MBP) lamps with wattages ≥ 25 and < 28;
- 2-foot, medium bipin U-shaped lamps with wattages ≥ 25 and < 28;
- 8-foot recessed double contact (RDC), rapid start, high output (HO) lamps not defined in ANSI Standard C78.1-1991;
- 8-foot RDC, rapid start, HO lamps (other than 0.800 nominal amperes) defined in ANSI Standard C78.1-1991; and
- 8-foot single pin (SP) instant start slimline lamps, with a rated wattage ≥ 52, not defined in ANSI Standard C78.3-1991.
- 4-foot T5, miniature bipin (MiniBP), straight-shaped, standard output (SO) lamps with rated wattage ≥ 26;
- 4-foot T5, MiniBP, straight-shaped, HO lamps with rated wattage ≥ 49;

DOE has also revised the existing definitions for "rated wattage" and "colored fluorescent lamp," as discussed in the final rule Federal Register notice.

#### 3.1.1.3 Incandescent Reflector Lamps

Section 321(30)(F) of EPCA (42 U.S.C. 6291(30)(F)) defines an incandescent reflector lamp as "a lamp described in subparagraph (C)(ii)" of the definition for incandescent lamp. Section 321(30)(C) of EPCA (42 U.S.C. 6291(30)(C)) defines "incandescent lamp" as:

"a lamp in which light is produced by a filament heated to incandescence by an electric current, including only the following:

(i) Any lamp (commonly referred to as lower wattage nonreflector general service lamps, including any tungsten-halogen lamp) that has a rated wattage between 30 and 199 watts, has an E26 medium screw base, has a rated voltage or voltage range that lies at least partially within 115 and 130 volts, and is not a reflector lamp.

[b] Section 316(b) of the Energy Independence and Security Act of 2007 amended section 321(30)(B)(viii) of EPCA (42 U.S.C 6291(30)(B)(viii)) by replacing the exclusion for lamps with a CRI of 82 or greater, with an exclusion of lamps with a CRI of 87 or greater.

(ii) Any lamp (commonly referred to as a reflector lamp) which is not colored or designed for rough or vibration service applications, that contains an inner reflective coating on the outer bulb to direct the light, an R, PAR, ER, BR, BPAR or similar bulb shapes with E26 medium screw bases, a rated voltage or voltage range that lies at least partially within 115 and 130 volts, a diameter which exceeds 2.25 inches, and has a rated wattage that is 40 watts or higher.

(iii) Any general service incandescent lamp (commonly referred to as a high- or higher-wattage lamp) that has a rated wattage above 199 watts (above 205 watts for a high wattage reflector lamp)."

As seen above in subparagraph (ii) of the definition of "incandescent lamp" contains several terms that limit scope of IRL. Appendix 3A contains statutory and CFR definitions for many of these terms. Concerning E26 medium screw bases, DOE will use the definition of "medium screw base" as added to EPCA in section 135(a)(3) of the Energy Policy Act of 2005 (EPACT 2005), Public Law 109-58. (42 U.S.C. 6291(51)) This defines an Edison screw base with the prefix E26 as that appearing in the "American National Standard for Electric Lamp Bases," ANSI/IEC C81.61–2003, published by the American National Standards Institute. This version of C81.61 identifies four lamp base (cap) types with a prefix of E26, which are single-contact medium screw (E26/24), double-contact medium screw (E26d), skirted medium screw for parabolic aluminized reflector (PAR) lamps (E26/50x39), and extended skirted medium screw for reflector (R)-lamps (E26/53x39).

## 3.2 MARKET ASSESSMENT

The following market assessment:

- identifies the manufacturer trade association and domestic manufacturers of GSFL and IRL;
- discusses manufacturer market share, regulatory programs, and non-regulatory initiatives;
- defines product classes;
- provides historical shipment data, shipment projections, and equipment lifetime estimates; and
- summarizes market performance data.

### 3.2.1 Trade Association

The National Electrical Manufacturers Association (NEMA) is the trade association of GSFL and IRL. In addition to lamps, NEMA's Lighting Systems Division also oversees products such as ballasts, emergency lighting, lighting controls, luminaires, solid state lighting, and other emerging lighting technologies. NEMA provides an organization through which manufacturers of lighting equipment can work together on projects that affect their industry and business. NEMA's activities relating to energy efficiency include:[1]

- "Advising DOE and executive agencies on lighting research and market transformation needs
- Participating in the climate change discussions with the Administration and Congress
- Monitoring energy-efficiency rulemakings and standards affecting lighting products by DOE and states
- Promoting the national voluntary luminaire rating and information program under the National Lighting Collaborative
- Supporting adoption of new ASHRAE/IESNA 90.1 lighting provisions
- Advising the DOE Federal Energy Management Program (FEMP) on energy-efficient lighting recommendations
- Coordinating with the DOE and Environmental Protection Agency on Energy Star® Buildings and Energy Star voluntary product labeling programs.
- Advocating market-based approaches to enhance the use and penetration of energy-efficient technologies."

### 3.2.2 Manufacturers and Market Share

The GSFL and IRL industries are characterized by both domestic and international manufacturers. The majority of covered GSFL and IRL are manufactured by three large companies. The three manufacturers that hold the majority of the domestic market share of GSFL and IRL are listed below.

- GE Consumer and Industrial of General Electric, Inc. (hereafter, "GE)
- OSRAM Sylvania of Siemens AG (hereafter "Osram")
- Philips Lighting of Royal Philips Electronics (hereafter "Philips")

In addition to lamps listed under this rulemaking, the lighting divisions of all three companies manufacture other products, such as lamp ballasts, high intensity discharge lamps, LED lighting, and compact fluorescent lamps (CFL).

#### 3.2.2.1 Small Businesses

Small businesses may be particularly affected by the promulgation of minimum energy conservation standards for fluorescent and incandescent lamps. The Small Business Administration (SBA) defines small business manufacturing enterprises for GSFL and IRL as having 1,000 employees or fewer.[2] SBA lists small business size standards that are matched to industries as they are described in the North American Industry Classification System (NAICS). A size standard is the largest that a for-profit concern can be and still qualify as a small business for Federal Government programs. These size standards are generally the average annual receipts or the average employment of a firm. For lamps, the size standard is matched to NAICS code 335110, Electric Lamp Bulb and Part Manufacturing, which has a size standard of 1,000 employees.

During its market survey, DOE contacted 57 companies that potentially manufactured lamps covered by this rulemaking. DOE determined that only 12 companies out of the 57 listed were potentially small business manufacturers of covered products. DOE contacted these potential small business manufactures to request an interview about the possible impacts on small business manufacturers. Of the 12 potential small business manufacturers, DOE interviewed four. Based on the information gathered during this process, DOE identified only one company as a small business manufacturer of covered GSFLs based on SBA's definition of small business manufacturer.

During its research and interviews, DOE learned valuable information about the overall market for GSFL and IRL. Small businesses in the GSFL and IRL industry are typically not manufacturers. If a small business does have any manufacturing, it typically manufactures fluorescent lamps and IRL that are not covered in this rulemaking. For example, small business fluorescent lamp manufacturers focus on signs, small fluorescent lamps, and vitamin D lamps, while the small business IRL manufacturers focus on products like rough service lamps. DOE found that most of the small businesses that sell covered GSFL and IRL are distributors and thus not small business manufacturers. These companies do not own any manufacturing equipment for the covered GSFL and IRL. Generally, these small businesses are lighting supply companies that source or rebrand products from a variety of overseas and domestic manufacturers. Even if a small distributor does offer its own brand of covered lamps, they typically contract with overseas factories to provide their products and are not involved in the manufacturing process.

DOE studied the potential impacts on small businesses in detail in the manufacturer impact analysis (see chapter 13 of the TSD for more details).

### 3.2.3 Regulatory Programs

DOE is aware of several Federal and international regulatory programs that affect the markets for GSFL and IRL. Amendments to EPCA in the Energy Policy Act of 1992 (EPACT1992), P.L. 102-486, established energy conservation standards for GSFL and IRL. (42 U.S.C. 6291(1) and 6295(i)(1)) In addition, subsequent amendments to EPCA in the Energy Independence and Security Act of 2007 (EISA 2007), P.L. 110-140, amended the existing standard for IRL.

The following section summarizes U.S. and Canadian regulatory initiatives relevant to the lamps covered by this rulemaking. While the following discussion is not exhaustive in describing all regulatory action related to GSFL and IRL, it provides detail on some notable initiatives that characterize recent developments in the lighting market.

#### 3.2.3.1 Federal Energy Conservation Standards

Table 3.1 shows the Federal standards that regulate 4-foot MBP, 2-foot U-shaped, 8-foot SP slimline, and 8-foot RDC HO general fluorescent lamps. The standards mandate that lamps manufactured on or after the specified effective dates must meet the minimum color rendering index (CRI) and minimum average lamp efficacy. 42 U.S.C. 6295(i)(1); 10 CFR Section

430.32(n)(1)

**Table 3.1 Federal Regulations for General Service Fluorescent Lamps**

| Lamp Type | Nominal Lamp Wattage<br>*W* | Minimum CRI | Minimum Average Lamp Efficacy<br>*lm/W* | Effective Date |
|---|---|---|---|---|
| Four-Foot Medium Bipin | > 35 W | 69 | 75.0 | Nov. 1, 1995 |
| | ≤ 35 W | 45 | 75.0 | Nov. 1, 1995 |
| Two-Foot U-Shaped | > 35 W | 69 | 68.0 | Nov. 1, 1995 |
| | ≤ 35 W | 45 | 64.0 | Nov. 1, 1995 |
| Eight-Foot Slimline | > 65 W | 69 | 80.0 | May 1, 1994 |
| | ≤ 65 W | 45 | 80.0 | May 1, 1994 |
| Eight-Foot High Output | > 100 W | 69 | 80.0 | May 1, 1994 |
| | ≤ 100 W | 45 | 80.0 | May 1, 1994 |

Fluorescent lamp ballasts are also regulated at the Federal level. Though they are not covered by this rulemaking, the ballast on which fluorescent lamps operate affects the systems' operating characteristics (total system power, lumen output, etc.) and therefore will affect the analyses DOE conducts. On September 19, 2000, DOE issued a Final Rule establishing energy conservation standards for ballasts that operate one F40T12 lamp, two F40T12 lamps, two F96T12 lamps, or two F96T12HO lamps (hereafter referred to as ''the Ballast Rule''). 65 FR 56740 (Sept. 19, 2000); 10 CFR 430.23(m)(4). Table 3.2 shows the energy conservation standards for fluorescent lamp ballasts. This rule bans the fabrication of ballasts that do not meet these ballast efficacy factor (BEF) requirements as of April 1, 2005. The ban on U.S. sales by ballast manufacturers to fixture manufacturers took effect July 1, 2005. The ban on U.S. sales of ballasts in lighting fixtures took effect on April 1, 2006. The ban on U.S. sales of replacement ballasts begins on July 1, 2010. The regulations provide for some exemptions.

**Table 3.2 EPCA Standards for Fluorescent Lamp Ballasts**

| Application for Operation of | Ballast Input Voltage<br>*V* | Total Nominal Lamp Watts<br>*W* | Ballast Efficacy Factor |
|---|---|---|---|
| One F40T12 Lamp | 120 | 40 | 1.805 |
| | 277 | 40 | 1.805 |
| Two F40T12 Lamps | 120 | 80 | 1.060 |
| | 277 | 80 | 1.050 |
| Two F96T12 Lamps | 120 | 150 | 0.570 |
| | 277 | 150 | 0.570 |
| Two F96 T12 HO Lamps | 120 | 220 | 0.390 |
| | 277 | 220 | 0.390 |

Sections 135(a) of EPACT 2005 amended EPCA to set additional requirements for fluorescent lamp ballasts operating one F34T12 lamp, two F34T12 lamps, two F96T12/ES lamps, or two F96T12HO/ES lamps (hereafter referred to as "the EPACT 2005 Ballast Standard"). (42 U.S.C. 6291(29) and 6295(g)(8)(a)) Table 3.3 outlines the EPACT 2005 Ballast Standards that DOE codified in the U.S. Code of Federal Regulations. (See 10 CFR 430.32(m)(5)) This standard effectively bans the fabrication of ballasts that do not meet these BEF requirements as of July 1, 2009. The effective ban on U.S. sales by ballast manufacturers to fixture manufacturers takes effect October 1, 2009. The effective ban on U.S. sales of ballasts in lighting fixtures takes effect on July 1, 2010. The ban on U.S. sales of replacement ballasts begins on October 1, 2010. EPACT 2005 provided some exemptions.

**Table 3.3 EPACT 2005 Standards for Fluorescent Lamp Ballasts**

| Application for Operation of | Ballast Input Voltage *V* | Total Nominal Lamp Watts *W* | Ballast Efficacy Factor |
|---|---|---|---|
| One F34T12 Lamp | 120 | 34 | 2.61 |
| | 277 | 34 | 2.61 |
| Two F34T12 Lamps | 120 | 68 | 1.35 |
| | 277 | 68 | 1.35 |
| Two F96T12/ES Lamps | 120 | 120 | 0.77 |
| | 277 | 120 | 0.77 |
| Two F96T12HO/ES Lamps | 120 | 190 | 0.42 |
| | 277 | 190 | 0.42 |

The Ballast Rule and the EPACT 2005 Ballast Standard effectively end the sale of magnetic ballasts that operate one F40T12 lamp, two F40T12 lamps, one F34 T12 lamp, two F34T12 lamps, or two F96T12/ES lamps. Although there are still magnetic ballasts that operate 8-foot RDC HO lamps, these ballasts are both less efficient and more expensive than their electronic counterparts.[3] Therefore, although the most common ballast installed in 2012 for T12 lamps are magnetic ballasts, the most common ballast sold after 2012 will likely be electronic T12 or electronic T8 ballasts.

In addition to Federal energy conservation standards for fluorescent lamps, EPCA also set Federal energy conservation standards for IRL. (42 U.S.C. 6295(i)(1)) Table 3.4 outlines these standards. EPCA mandated that all lamps manufactured after November 1, 1995 meet six efficacy requirements. Minimum lamp efficacy varies by nominal lamp wattage. One effect of these standards is increased use of higher efficacy halogen lamps as a replacement for standard IRL. EISA 2007 amended EPCA's definition for incandescent reflector lamp and amended the standard in 42 U.S.C. 6295(i)(1). Prior to EISA 2007, the statutory definition for IRL excluded elliptical reflector (ER) and bulged reflector (BR) shaped lamps and lamps with a diameter less than 2.75 inches. However, EISA 2007 amended this definition to include ER and BR shaped lamps and lamps with diameter greater than 2.25 inches. EISA 2007 also amended 42 U.S.C. 6295(i)(1) to exempt the following lamps from the minimum efficacy requirements: (1) lamps rated at 50 watts of less that are ER30, BR30, BR40, and ER40; (2) lamps rated at 65 watts that are BR30, BR40, or ER40 lamps; and (3) R20 incandescent reflector lamps rated 45 watts or less.

**Table 3.4 Federal Regulations for Incandescent Reflector Lamps**

| Nominal Lamp Wattage *W* | Minimum Average Lamp Efficacy *lm/W* |
|---|---|
| 40-50 | 10.5 |
| 51-66 | 11.0 |
| 67-85 | 12.5 |
| 86-115 | 14.0 |
| 116-155 | 14.5 |

| | |
|---|---|
| 156-205 | 15.0 |

### 3.2.3.2 Canadian Energy Efficiency Standards

The Natural Resources Canada (NRCan) Office of Energy Efficiency regulates the energy efficiency of GSFL and IRL in Canada. In 1992, Parliament passed the Energy Efficiency Act (S.C. 1992, c. 36), which concerns minimum performance levels for energy-using products, effective February 1995. In November 1995, Canada's *Energy Efficiency Regulations* (SOR/94-651) were amended to include GSFL and some GSIL. An amendment in April 2003 included regulation of selected ER and BR IRL.

Canada's approach to the regulation of GSFL closely resembles the U.S. Federal Efficiency Standard discussed in section 3.2.3.1. The Canadian minimum average CRI and lamp efficacy levels are identical to those shown in Table 3.1. Though there are minor variations in definition between the U.S. and Canadian standards, they effectively cover the same product.

The Canadian test procedures refer to a document published by the Canadian Standards Association (CSA). CSA is an independent standards-setting agency that establishes test procedures and efficiency standards that are typically adopted by the Canadian government. Fluorescent lamp test procedure CAN/CSA-C819-95 (2001), entitled *Performance of General Service Fluorescent Lamps*, references applicable ANSI, CIE, and IES standards.

Canada's approach to regulating IRL differs from the U.S. approach. Similar to the United States, Canada covers R, PAR, and lamps with similar bulb shapes. However, Canada also regulates selected ER and BR lamps. The Energy Efficiency Regulations of Canada apply to three categories of IRL: general service incandescent reflector lamps, BR lamps, and ER lamps. A "general service incandescent reflector lamp" is defined as an:

"Incandescent reflector lamp

"a. with an R bulb shape, a PAR bulb shape or a bulb shape similar to R or PAR that is neither ER nor BR, as described in ANSI C79.1,
b. with an R bulb shape, a PAR bulb shape or a bulb shape similar to R or PAR that is neither ER nor BR, as described in ANSI C79.1,
c. with a nominal voltage or voltage range that lies at least partially between 100 volts and 130 volts,
d. with a diameter greater than 70 mm (2.75 inches), and
e. that has a nominal power of not less than 40 W and not more than 205 W, but does not include:
f. a coloured incandescent reflector lamp, or
g. an incandescent reflector lamp that
   i) is of the rough or vibration service type with:
      (A) a C-11 filament, as described in the IES Handbook, with five supports exclusive of lead wires,
      (B) a C-17 filament, as described in the IES Handbook, with eight supports exclusive of lead wires, or
      (C) a C-22 filament, as described in the IES Handbook, with 16 supports exclusive of lead wires,

(ii) is of the neodymium oxide type and has a lens containing not less than 5% neodymium oxide,
(iii) has a coating or other containment system to retain glass fragments if the lamp is shattered and is specifically marked and marketed as an impact-resistant lamp,
(iv) is specifically marked and marketed for plant growth use and has a spectral power distribution that:
(A) is different from that of the lamps described in paragraphs (a) to (e), and
(B) contains a filter that suppresses yellow and green portions of the spectrum, or
(v) is specifically marked and marketed
(A) as an infrared heat lamp,
(B) for heat-sensitive use,
(C) for mine use,
(D) for marine, aquarium, terrarium or vivarium use, or
(E) for airfield, aircraft or automotive use."

BR lamps are defined as:

"Incandescent reflector lamp as described in ANSI C79.1, but does not include any of those lamps that have

a. a diameter of 95.25 mm (BR30) and a nominal power of less than 66 W,
b. a diameter of 92.5 mm (BR30) and a nominal power of 85 W, or
c. a diameter of not less than 120.65 ,mm(BR38) but not more than 127 ,mm (BR40) and a nominal power of less than 121 W."

ER lamps are defined as IRL as described in ANSI C79.1. Table 3.5 shows the Canadian energy conservation standards for IRL. In addition to the referenced ANSI documents in the definitions, the Canadian test procedures reference CAN/CSA-C862-01, *Performance of Incandescent Reflector Lamps*. The standards became effective on April 1, 1996 for GSFL and IRL and on January 1, 2003 for additional ER and BR lamps.

**Table 3.5 Canadian Energy Efficiency Regulations for Incandescent Reflector Lamps**

| **Rated Wattage**<br>*W* | **Minimum Average Lamp Efficacy**<br>*lm/W* |
|---|---|
| **ER Lamps** | |
| 50 | 7.0 |
| 75 | 6.5 |
| 120 | 10.0 |
| **R, PAR, BR Lamps, and ER Lamps Not Covered Above** | |
| 40-50 | 10.5 |
| 51-59 | 11.0 |
| 60-85 | 12.5 |
| 86-115 | 14.0 |
| 116-155 | 14.5 |
| 156-205 | 15.0 |

In November 2006, NRCan published a bulletin proposing to amend Canada's Energy Efficiency Regulations. NRCan proposed testing and labeling requirements for light output, input wattage, and rated lifetime for GSFL, medium base, integrally ballasted CFLs, and reflector and non-reflector GSIL.[4] The bulletin also proposed a definition for non-reflector GSIL.

### 3.2.4 Non-Regulatory Initiatives

DOE reviewed several national, regional, and local voluntary programs that promote the use of energy-efficient lighting in the United States. FEMP's program for energy-efficient lighting, the Consortium for Energy Efficiency (CEE)'s High Performance Commercial Lighting Initiative, the Energy Efficient Commercial Buildings Deduction, and the Northeast Energy Efficiency Partnership (NEEP) are a few examples. The following section summarizes some of these programs for the lamps covered by this rulemaking. While it is not an exhaustive list, the discussion provides detail on some notable initiatives that characterize recent developments in the lighting market.

#### 3.2.4.1 Federal Energy Management Program

FEMP helps Federal buyers identify and purchase energy-efficient products including certain GSFL. Section 161 of EPACT 1992 encourages energy-efficient Federal procurement. Executive Order 12902 and FAR section 23.704 direct agencies to purchase products in the upper 25 percent of energy efficiency. As Table 3.6 shows, FEMP provides recommendations of total light output (in lumens) and the best available models at the time of publishing.[5] FEMP offers buyers support tools such as efficiency guidelines, cost-effectiveness examples, and a cost calculator. FEMP also offers training, on-site audits, demonstrations, and design assistance.

**Table 3.6 Federal Energy Management Program Efficiency Recommendation**

| Lamp Type | Recommended | Best Available |
|---|---|---|
| Four-Foot T8, 32W | 2,800 lumens or more | 3,000 lumens |
| Four-Foot T12, 34W | 2,800 lumens or more | 2,900 lumens |
| Eight-Foot T8, 59W | 5,700 lumens or more | 5,950 lumens |
| Eight-Foot T12, 60W | 5,600 lumens or more | 6,000 lumens |
| T8/U, 31-32w | 2,600 lumens or more | 2,850 lumens |
| T12/U, 34w | 2,700 lumens or more | 2,760 lumens |

#### 3.2.4.2 Consortium for Energy Efficiency

CEE has both a Residential Lighting Initiative and a High-Performance Commercial Lighting Initiative. The Residential Lighting Initiative primarily promotes high efficiency fixtures and CFLs, neither of which is covered under this rulemaking. The purpose of CEE's High-Performance Commercial Lighting Initiative is to define what constitutes "high performance," and the initial efforts have focused on efficient T8 lighting products. On May 1, 2007, CEE updated its specification for high-performance T8 lamps as a T8 lamp not greater than 32W with a minimum initial lamp lumens of 3,100 lumens or greater.[6] On January 23, 2007, CEE released its specification for reduced-wattage T8 lamps as a lamp of 25W or 28W with minimum initial lumen output greater than or equal to 2,585 lumens or 2,400 lumens, respectively.[7]

#### 3.2.4.3 Energy Efficient Commercial Building Deduction

EPACT 2005 created the Energy Efficient Commercial Buildings Deduction (26 U.S.C 179D), which establishes a tax deduction for building owners who incur expenses for energy efficiency upgrades. Effective for property in service from January 1, 2006 through December 31, 2008, the deduction allows partial deductions for improvement in interior lighting. Though the statute does not specify required lamp types or efficacies, it does call for an overall reduction in lighting power density, encouraging the use of higher performance and reduced-wattage GSFL. The Emergency Economic Stabilization Act of 2008 (HR-1424), approved and signed on October 3, 2008, extends the benefits of EPACT 2005 through December 31, 2013.

#### 3.2.4.4 Northeast Energy Efficiency Partnerships

Northeast Energy Efficiency Partnerships (NEEP) is a regional nonprofit organization that promotes energy efficiency in the Northeast. NEEP currently runs a High Efficiency Commercial Lighting Initiative to "achieve cost-effective energy and demand by overcoming market barriers to the availability and widespread market adoption of advanced T8 fluorescent lighting systems."[8] NEEP coordinates with multiple local and state governments, utilities, and other initiatives, such as Efficiency Vermont and the Long Island Power Authority, to promote efficient lighting products. Efficiency Vermont offers technical assistance and financial incentives to encourage energy efficiency in Vermont. This organization offers rebates of $15 for the installation of "Super T8" lamp-and-ballast systems. It also provides a custom rebate for reduced-wattage T8 lamps.[9] The Long Island Power Authority is a non-profit municipal electric utility that serves the Long Island area. It provides rebates for high-performance T8 systems and T5 fixtures ranging from $10 to $35.[10]

### 3.2.5 Historical Shipments

Awareness of annual product shipment trends is an important aspect of the market assessment and the development of the standards rulemaking. For this rulemaking, NEMA publicly provided historical shipments of GSFL and IRL from 2001 to 2005 and confidential shipments for 2006 to 2007.[11] DOE used this data for three main purposes. First, the shipment data and market trend information contributed to the shipments analysis and base-case forecast for GSFL and IRL (see chapter 9). By using historical shipment data and expert opinion on market trends, and calibrating forecast assumptions with recent data, DOE believes that the shipments model and base-case forecasts are based on a sound dataset. Second, DOE used the data to select the representative product classes and representative units for analysis. Generally, DOE selected representative product classes and units for analysis to reflect the highest volume, most common lamp types and wattages used in the United States today (see chapter 5). Third, DOE used the data to develop the market share matrices for the national impact analysis (see chapter 10). Based on its understanding of trends in the market, DOE estimated how the market would respond to the various trial standard levels.

For GSFL, the historical shipment data is broken down by lamp length (2-foot, 4-foot, and 8-foot), diameter (T12, T8, and T5), shape (linear and U-shaped), and in some cases, lumen output (SO or HO). Four-foot MBP lamps constitute the vast majority of GSFL sales. These are followed in order of unit sales by 8-foot SP slimline lamps and 8-foot RDC HO lamps, which together constitute under a quarter of GSFL sales. Four-foot MBP, 8-foot SP slimline, and 8-foot RDC HO lamps are the most common GSFL. Shipments of 2-foot U-shaped lamps account for less than 5 percent of GSFL unit sales historically. DOE received confidential shipments for 4-foot T5 MiniBP SO and HO GSFL. DOE's research also indicated that 4-foot MiniBP SO and HO lamps constituted at least 2 percent of all GSFL shipments in 2004, and that this market share was growing.[12]

GSFL in the categories of 4-foot MBP, 8-foot SP slimline, and 2-foot U-shaped lamps are primarily used in the commercial sectors. As Table 3.7 shows, 4-foot MBP fluorescent lamp shipments show a clear decrease in the T12 market share and an increase in the T8 market share. These shipments, coupled with information obtained from NEMA and manufacturers, suggest that consumers are moving away from 4-foot T12 fluorescent lamps and toward 4-foot T8 fluorescent lamps. This trend is reflected both in the popularity of T8 lamps in new construction and in lighting system retrofits and renovations where the ballast is replaced. The vast majority of 4-foot T12 ballasts are magnetic, while the vast majority of 4-foot T8 ballasts are electronic. This decline of 4-foot T12 shipments will most likely be compounded in 2010 when new energy conservation standards for fluorescent ballasts, including replacement F40T12 ballasts and new F34T12 ballasts, go into effect. (See 10 CFR 430.32(m)(4)(ii) and 430.32(m)(5)-(6)) For 4-foot F40T12 and F34T12 lamps, discussions with manufacturers suggest that they anticipate their customers will shift to T8 counterparts instead of T12 lamps that operate with electronic ballasts.

**Table 3.7 NEMA Shipments of Four-Foot Medium Bipin General Service Fluorescent Lamps**

| | **Unit Sales by Year** *thousands* | | | | |
|---|---|---|---|---|---|
| | **2001** | **2002** | **2003** | **2004** | **2005** |
| T12 Four-Foot Medium Bipin | 212,564 | 205,998 | 181,931 | 175,850 | 162,664 |
| T8 Four-Foot Medium Bipin | 164,129 | 163,632 | 172,294 | 195,698 | 215,530 |
| Total Four-Foot Medium Bipin | 376,593 | 369,630 | 354,225 | 371,548 | 378,194 |

As Table 3.8 shows, historical shipments of 8-foot GSFL reflect a decline in shipments of 8-foot T12 lamps and an increase in shipments of 8-foot T8 lamps. However, this increased market share in 8-foot T8 lamps does not sufficiently compensate for the decreased shipments of 8-foot T12 lamps. Discussions with NEMA, manufacturers, and lighting experts suggest that a portion of the 8-foot T12 market is being transferred to the 4-foot T8 market. However, because the lumen output from a conventional 8-foot lamp-and-ballast system is significantly higher than that of a 4-foot lamp-and-ballast system, it is likely that one 8-foot system containing two lamps will be replaced by two 4-foot systems, each containing two lamps. It is therefore possible that any standard affecting shipments of T12 8-foot SP slimline GSFL may also notably affect the shipments of T8 4-foot MBP GSFL.

**Table 3.8 NEMA Shipments of Eight-Foot Single Pin Slimline General Service Fluorescent Lamps**

| | Unit Sales by Year *thousands* | | | | |
|---|---|---|---|---|---|
| | **2001** | **2002** | **2003** | **2004** | **2005** |
| T12 Eight-Foot Single Pin Slimline | 43,265 | 41,443 | 37,170 | 36,263 | 33,636 |
| T8 Eight-Foot Single Pin Slimline | 4,405 | 5,300 | 5,183 | 5,727 | 5,176 |
| Total Eight-Foot Single Pin Slimline | 47,670 | 46,743 | 42,353 | 41,990 | 38,812 |

Table 3.9 shows the historical shipments of 2-foot U-shaped GSFL. While no clear trend can be seen in the market share progression of U-shaped T12 and T8 lamps, the market share of U-shaped lamps is small compared to that of 4-foot MBP and 8-foot SP slimline lamps.

**Table 3.9 NEMA Shipments of Two-Foot U-Shaped General Service Fluorescent Lamps**

| | Unit Sales by Year *thousands* | | | | |
|---|---|---|---|---|---|
| | **2001** | **2002** | **2003** | **2004** | **2005** |
| T12 Two-Foot U-Shaped | 9,672 | 9,314 | 9,460 | 7,014 | 8,839 |
| T8 Two-Foot U-Shaped | 8,014 | 6,784 | 7,018 | 9,224 | 8,659 |
| Total Two-Foot U-Shaped | 17,686 | 16,098 | 16,478 | 16,238 | 17,496 |

While 4-foot MBP, 8-foot SP slimline, and 2-foot U-shaped lamps are primarily used in the commercial sector, 8-foot HO lamps are primarily used in the industrial sector for applications such as high-bay lighting. Table 3.10 shows the historical shipments of 8-foot HO lamps. Discussions with experts and manufacturers indicate that most of the RDC HO lamps currently sold are used with electronic ballasts. The market share of 8-foot RDC HO is relatively small compared to that of 4-foot MBP and 8-foot SP slimline lamps. As seen in NEMA's shipment data, T12 8-foot RDC HO lamps have the majority of the RDC HO market. Discussions with lighting experts and lamp manufacturers indicate that they expect any migration of the 8-foot RDC HO market to go toward T5 fluorescent lamps and metal halide lamps.

**Table 3.10 NEMA Shipments of Eight-Foot Recessed Double Contact High Output General Service Fluorescent Lamps**

| | Unit Sales by Year *thousands* | | | | |
|---|---|---|---|---|---|
| | **2001** | **2002** | **2003** | **2004** | **2005** |
| T12 Eight-Foot Recessed Double Contact HO | 23,887 | 24,398 | 24,206 | 24,591 | 25,442 |
| T8 Eight-Foot Recessed Double Contact HO | 691 | 647 | 467 | 674 | 420 |
| Total Eight-Foot Recessed Double Contact HO | 24,578 | 25,045 | 24,673 | 25,265 | 25,862 |

IRL are primarily used in the commercial and residential sectors. Based on interviews with lighting experts, DOE estimates that approximately 80 percent of halogen IRL are used in the commercial sector and 20 percent are used in the residential sector. DOE also estimates that 20 percent of the incandescent (i.e., non-halogen) reflector lamps are used in the commercial sector, and that the balance (80 percent) is used in the residential sector. As Table 3.11 shows, historical shipment data indicates that the total market share of halogen IRL is growing. However, its slow rate of growth suggests either that the market has reached near equilibrium or that competing incandescent IRL are successfully gaining market share and new installation opportunities. The shipment data in Table 3.11 reflect this trend, indicating comparatively large growth among non-halogen IRL, in contrast to the relatively flat growth for halogen IRL.

**Table 3.11 NEMA Shipments of Incandescent Reflector Lamps**

| | **Unit Sales by Year** *thousands* | | | | |
|---|---|---|---|---|---|
| | **2001** | **2002** | **2003** | **2004** | **2005** |
| PAR Incandescent | 8,900 | 6,697 | 5,090 | 5,308 | 15,018 |
| R Incandescent | 89,465 | 96,218 | 103,407 | 111,720 | 124,641 |
| PAR 38 Halogen | 40,804 | 45,938 | 45,673 | 49,937 | 46,329 |
| PAR 30 and PAR 20 Halogen | 32,523 | 27,128 | 30,506 | 35,567 | 39,985 |
| Total Incandescent Reflector Lamps | 171,692 | 175,961 | 184,676 | 202,532 | 225,973 |

## 3.3 TECHNOLOGY ASSESSMENT

The purpose of the technology assessment is to develop a preliminary list of technologies that could be used to improve the efficacy of GSFL and IRL. The following assessment provides brief descriptions of the basic construction and operation of each lamp type, followed by a discussion of technology options to improve the efficacy of that lamp type.

### 3.3.1 General Service Fluorescent Lamps

The fluorescent lamp is a low pressure gas discharge source. The lamp consists of a glass bulb or tube, filled with low pressure mercury vapor and inert gas, with electrodes sealed onto both ends of the tube. An arc, in the form of primarily ultraviolet (UV) radiation, is produced by current flowing between the two electrodes. The phosphors coating the bulb's inner wall then absorb this UV radiation and emit light in the visible spectrum. The fluorescent lamp has five major components in its construction: bulb, electrodes, base, gas fill, and phosphors.

Fluorescent lamp bulbs can be manufactured in a variety of shapes and sizes. The GSFL lamps in this rulemaking include 4-foot and 8-foot linear lamps and 2-foot U-shaped lamps. Changing the shape of the lamp can alter the overall efficacy as the lamp may require a different voltage to maintain the discharge and UV radiation. In addition, the length of a lamp also influences its efficacy. As Figure 3.3.1 shows, the greater the length, the higher the efficacy, since losses associated with the electrodes are essentially constant. Therefore, a longer arc length will have less electrode power loss relative to the total losses. However, because different lamp shapes and lengths may provide different utility to the consumer and also depend on the lighting fixture, DOE is not considering these properties as technology options. Rather, as indicated in the discussion of product classes in Section 3.4, product classes differentiate lamps by their shape and length.

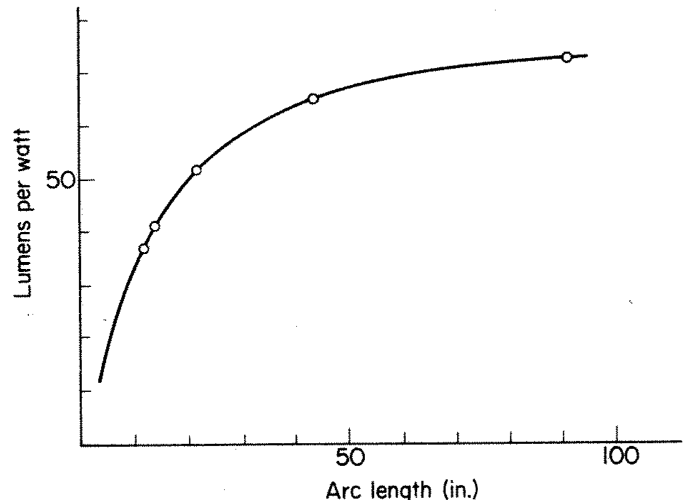


**Figure 3.3.1 Lamp Length Effects on Efficacy**
Source: IESNA Lighting Handbook: Reference & Application[13]

Two electrodes are hermetically sealed to both ends of the bulb. The electrodes are usually constructed from coiled tungsten wires coated with a mixture of alkaline oxides. A base provides an electrical connection to these electrodes and also supports the lamp. Depending on the start method and operational properties of the lamp (e.g., dimming, wattage, etc.), lamp designs may use different bases such as SP, MBP, and RDC. In its analysis, DOE determined that base type and size has little to no effect on efficacy and therefore did not consider these as technology options. Once voltage is applied to the electrodes, the tungsten coil and coatings emit large quantities of electrons when the coating is at the proper temperature (1,000–1,300 K). These electrons then collide with gaseous mercury atoms, exciting electrons within those atoms. As the electrons decay to their stable or ground state, they emit UV radiation primarily at 254 nanometers (nm). In addition to the mercury vapor, an inert gas or a combination of gases is added to the lamp primarily to moderate the collisions of mercury ions and minimize evaporation of the electrode coating. As discussed above, the UV radiation is then absorbed by the phosphors and reemitted as light.

A fluorescent lamp must be operated in series with a current-limiting device, which is usually a magnetic or electronic ballast. Each ballast has an associated BF that affects the total light output of the fluorescent lamp. In addition to limiting current, ballasts also supply starting and operating voltages required by the lamp. Some ballasts also preheat the electrodes before initiating the arc. Magnetic fluorescent lamp ballasts use a variety of starting methods, including preheat start, instant start, or rapid start.[c] Electronic ballasts can also use a variety of starting

[c] In the preheat start method, usually used with bipin bases, a current passes through both electrodes in series, heating them. A thermal switch then opens to apply a voltage applied across the lamp and induces the arc. Instant starting, usually used with a single pin base and with no heating of the electrodes, involves a high voltage (400V to 1,000V) applied across the lamp. This voltage causes the ejection of electrons from the electrodes, creating the arc discharge. The arc current subsequently heats the electrodes. Rapid start lamps, operating on a bipin base, can also be instant started and operate similarly. However, in rapid start, the electrodes are continuously actively heated during operation by passing a small current to each of the electrodes while maintaining a voltage difference across the lamp.

methods, including instant start, rapid start, and programmed start.[d] Because different starting methods result in changes in lamp efficacy, the test procedure for GSFL requires that the efficacy of each lamp is measured using a common starting method and ballast. However, DOE considers different starting methods in its analysis. For example, DOE pairs base case 4-foot T12 MBP lamps with magnetic, rapid-start ballasts, and base case 4-foot T8 MBP lamps with electronic, instant-start ballasts. Magnetic and electronic ballasts are also available in a variety of lamp-per-ballast designs. For example, electronic ballasts are typically manufactured in 1-, 2-, 3-, and 4-lamp versions.

In discussing each of the following technology options, it is important to note that the efficacy of a lamp, in lumens per watt (lm/W), can be affected in two major ways. One method is by affecting the total light output at a given wattage. This generally refers to changing the spectral output of the lamp to result in a larger overlap with the spectral eye sensitivity.[e] The second method of changing lamp efficacy is requiring a different electrical wattage input to maintain a given lumen output. This method involves tweaking the processes that convert electrical energy to visible radiation.

#### 3.3.1.1 Highly Emissive Electrode Coatings

Fluorescent lamp electrodes are generally tungsten filaments coated with a mixture of alkaline earth oxides. The purpose of the electrodes is to emit a sufficient number of electrons to ionize the gas and maintain the lamp discharge. Therefore, any improvement in electrode coating that would allow electrons to be more easily removed from the electrodes would reduce the lamp power and increase the overall efficacy of the lamp. This technology option essentially addresses the efficiency of the conversion of electrical input power to visible radiation. As electrons are more easily emitted from the electrodes, a lower voltage is needed to maintain the arc. Conventional emissive coatings include barium oxide (BaO), calcium oxide (CaO), and strontium oxide (SrO). In addition to raising efficacy, the electrode coatings can result in an increased lamp lifetime. Without sufficient electron emission from the electrode, a large voltage gradient is created in front of the electrode during the cathode cycle, which is emitting negatively charged ions and receiving positively charged ions. This high electric field accelerates these ions into the electrode at a high velocity, causing electrode damage. The damage shortens the lifetime of the lamp. Additional materials have been mixed with existing conventional oxides to coat fluorescent lamp electrodes. These materials include zirconium oxide (ZrO), which extends lamp lifetime, and silicon carbide (SiC), which more effectively removes electrons from the electrode.

#### 3.3.1.2 Higher Efficiency Lamp Fill Gas Composition

Fluorescent lamps contain mercury vapor, which when ionized produces UV radiation. They also contain a rare gas or combination of gases to facilitate ignition. These “lamp fill gases” affect the mobility of the mercury ions and electrons in the lamp plasma based on their

[d] Programmed start ballasts delay the starting voltage until the electrodes are heated to an optimum temperature. Then, they may reduce the voltage on the electrodes.
[e] A “lumen” is a measurement of the radiometric energy emission from a light source weighted by the response function of a human eye, called the photopic spectral luminous efficiency function, V(λ). See Figure 3.3.4 for a graph if this function.

molecular weight. Lower molecular weight gases generally result in higher lamp efficacy. As lighter gases are used, the mobility of mercury ions and electrons increases, allowing them to reach greater velocities. This causes a rise in electron temperature of the plasma, facilitating recombination and ultimately raising the UV radiation to saturation level. However, if the mobility of the ions and electrons exceeds a certain optimal point, they are then able to reach the lamp glass surface, which prevents emission and effectively reduces UV output.

Standard lamps generally use argon gas. Energy-saver lamps may use a mixture of krypton and argon. In addition, neon and xenon are sometimes blended with argon. As Figure 3.3.2 shows, given a linear power density of 25 watts/foot (W/ft), both neon and argon result in similar UV radiation. However, given a high linear power density of 50 W/ft, neon clearly allows for higher UV radiation, and therefore higher efficacy.

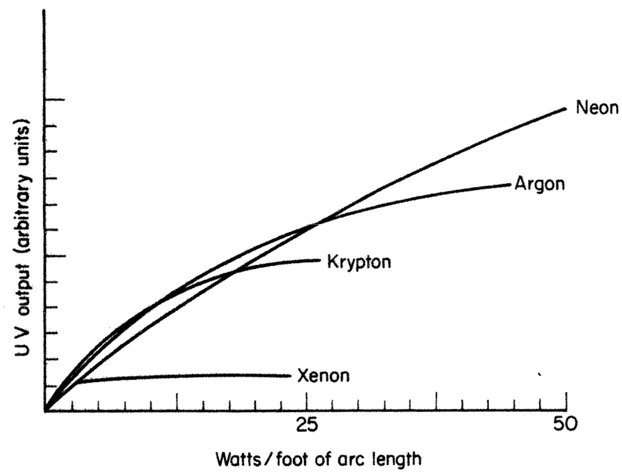


**Figure 3.3.2 Lamp Fill Gas Effect on UV Output for T12 Lamps**
Source: Electric Discharge Lamps [14]

These gases are usually at low pressures, ranging from 100 to 400 Pascals. As the pressure exceeds a certain point, elastic scattering increases, decreasing the mobility of the ions and electrons. This decreased mobility lowers the total UV radiation of the lamp, thereby decreasing lamp efficacy. Because fluorescent lamp ballasts are often current-controlled devices, the use of higher efficiency lamp fill gases, such as krypton, results in lower power. These lower power lamps, often called energy-saver lamps, have some restrictions of usage, such as operation in less than 60 degree Celsius ambient temperature, with reduced current ballasts, and with rapid-start ballasts, etc.

Lamp fill gas composition can also affect lamp lifetime due to collisions between the lamp fill gas and the evaporated electrode coatings. As discussed earlier, one common emissive coating used on electrodes is barium oxide (BaO). During lamp operation the BaO coating slowly evaporates from the surface of the electrode. However, some of these escaped barium atoms then collide with the lamp fill gas, propelling them back toward the electrode and redepositing them. As Figure 3.3.3 shows, the relative thermionic emission for the cathode, a measure of the number of electrons emitted, is much greater for a larger molecular weight gas such as krypton than for a lighter gas such as neon. This is because a larger mass atom can more effectively collide with and change the trajectory of the barium atoms, providing a lower diffusion rate of the barium atoms away from the electrode. This redeposition of the electrode coating results in a longer lamp lifetime.

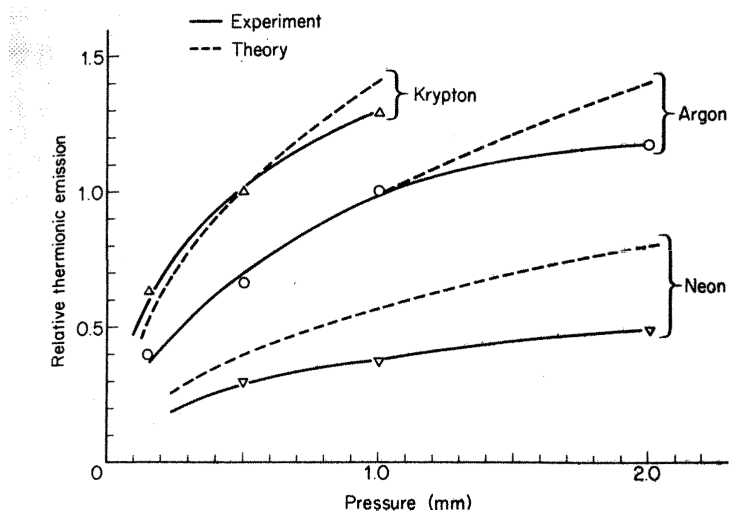


**Figure 3.3.3 Lamp Fill Gas Effect on Thermionic Emission for T12 Lamps**
Source: Electric Discharge Lamps [15]

### 3.3.1.3 Higher Efficiency Phosphors

As described earlier, the main purpose of phosphor in a fluorescent lamp is to absorb the UV radiation and reemit it as visible radiation. Therefore, one method of improving lamp efficacy is to increase phosphor efficiency. This can be done by increasing the phosphor's UV absorption or by increasing its emission of radiation in the visible spectrum. Lamp efficacy can also be improved by increasing the thickness of the phosphor layer, also called phosphor weight.

Typically, there are efficiency losses in the phosphor's conversion of UV radiation to visible radiation, or light. Some of these losses are related to the extent to which the phosphors emit light in the visible spectrum (i.e., radiation with wavelengths between 400 to 750 nanometers (nm)) and the extent that they radiate at visually sensitive wavelengths.

The human eye does not have the same level of sensitivity to all wavelengths of light. For example, the eye is highly sensitive to light emission around 550 nanometers (nm), but less sensitive to emission at 450nm or 650nm. The photopic luminous efficiency function, V(λ), represents the response function of the human eye to light. Figure 3.3.4 depicts V(λ).

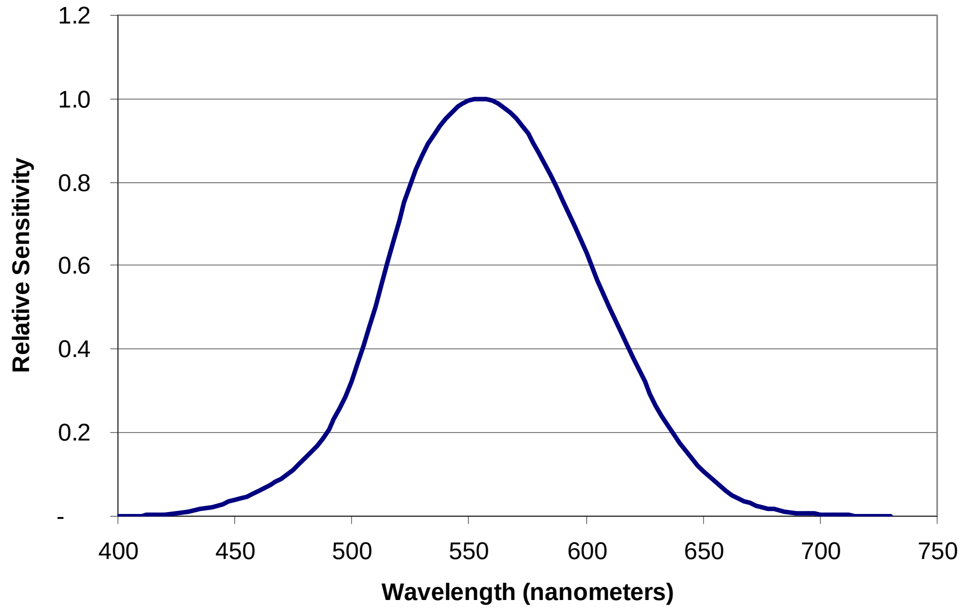


**Figure 3.3.4 Human Eye Photopic Spectral Luminous Efficiency Function, V(λ)**

Lumens, used to calculate lamp efficacy, measures the radiometric energy emission from a light source weighted by the response function of the human eye, V(λ). Therefore, the specific wavelengths that a lamp emits will affect the lamp's calculated efficacy. In other words, because the human eye is less responsive to certain wavelengths of light, such as those in the blue spectrum, those lamps that contain these less sensitive wavelengths will have lower efficacies. As such, every watt of radiometric energy emitted from a fluorescent lamp is not equal under a lumen-per-watt metric.

The spectral power distribution (SPD) of light emitted from a lamp characterizes the amount of power radiated at each wavelength in the visible spectrum. Figure 3.3.5 illustrates a sample SPD. It is apparent that the light source emits more radiation at certain wavelengths than others.

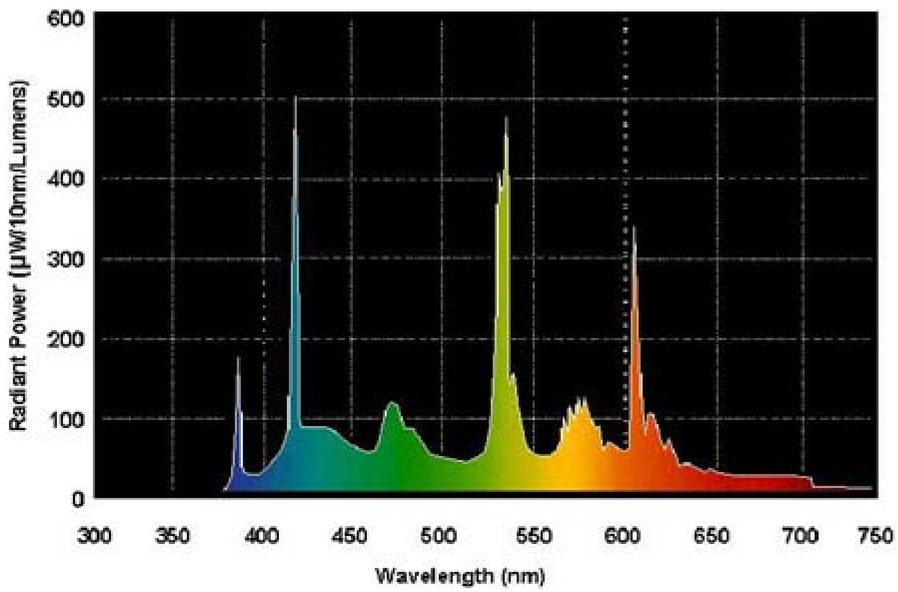


**Figure 3.3.5 Sample Power Spectrum Distribution**

Source: www.gelighting.com[16]

This SPD determines the color correlated temperature (CCT) and the color rendering index (CRI), both important properties for measuring the color quality of light. CRI, a single value with no units, is a measure of the color rendering properties of a light source, or the ability of a light source to show the "true" color of an object as compared to a reference source.[f 17] The maximum CRI is 100. Lower CRI values indicate greater variation in an object's apparent color compared to when lit by the reference source. CCT, a single value with units of degrees Kelvin (K), is a measure of the color appearance of light emitted from a lamp.[g,h,18] Lower CCT values correspond to warmer light, with more red content in the spectrum, and higher CCTs correspond to cooler light, with more blue content. As the spectral emission from the lamp is modified to change the CCT, the light emitted often contains more red or blue light.

Given the shift in the wavelengths of light emitted from lamps with different CCTs, and the fact that lumens account for the amount of light emitted at particular wavelengths, the efficacy of lamps with different CCT can vary. For lamp spectra with very high or very low CCTs, the spectral emission of the lamp will not be tuned to the photopic luminous efficiency function $V(\lambda)$ for maximum luminous efficacy. Therefore, in principle, CCTs lower than about 3,000K and higher than about 5,000K will be less efficacious than those between 3,000K and

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[f] According to the IESNA Lighting Handbook, the CRI of a light source is "a measure of the degree of color shift objects undergo when illuminated by the light source as compared with those same objects when illuminated by a reference source of comparable color temperature."

[g] According to the IESNA Lighting Handbook, the CCT of a light source is "the absolute temperature of a blackbody whose chromaticity most nearly resembles that of the light source."

[h] While CCT is a single value, light with the same CCT value may have slightly different properties. Therefore, the lighting industry has defined elliptical regions in chromaticity space (called 4 MacAdam color steps) for specific CCT values (e.g., 2,700K, 3,000K, 3,500K, 4,000K/4,100K, 5,000K, and 6,500K) in ANSI C78.376-2001. These regions act as a tolerance for the color properties of the lamp.

5,000K. Figure 3.3.6 illustrates the difference in average efficacy between 32W T8 4-foot MBP GSFL with different CCTs (and other attributes equivalent).

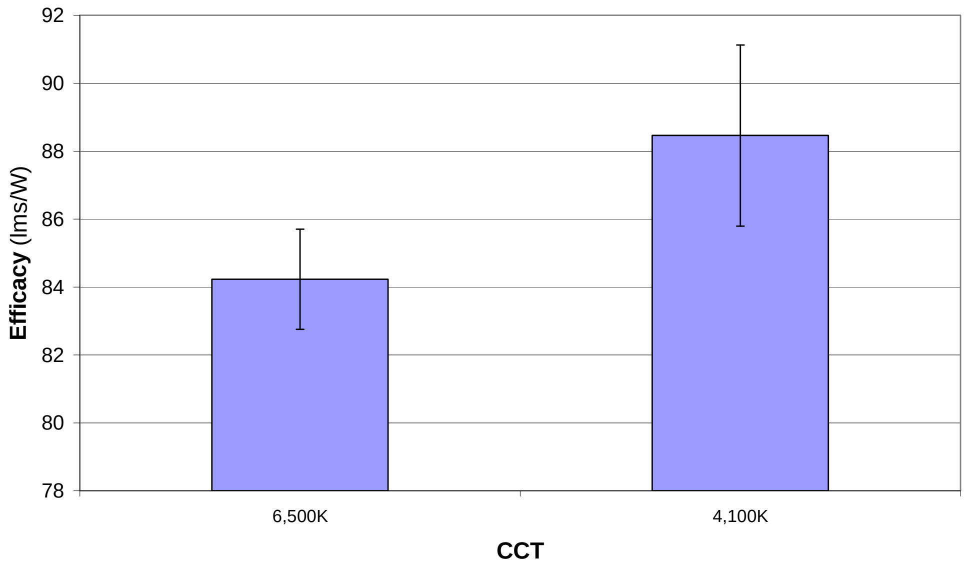


**Figure 3.3.6 Average Efficacies of Lamps with a CCT of 6,500K versus 4,100K**

Different types of phosphor emit light with different SPDs, and the choice of phosphor or blend of phosphors greatly affects the color of the lamp. There are two groupings of phosphors: halophosphors and rare-earth phosphors (often called tri-phosphors). Initially, halophosphors, typically composed of group 17 elements from the periodic table of elements, were predominantly used in fluorescent lamps. Then, in the late 1980s, rare-earth phosphors, which are generally considered to have higher phosphor efficiencies, better color rendering properties, and improved lumen maintenance, were integrated into the lamps. Many fluorescent lamps now use three narrow-band, rare-earth phosphors that emit light in the short, middle, and long wavelength ranges of the visible spectrum. As Figure 3.3.7 shows, the introduction of these three-band lamps resulted in a marked increase in efficacy. However, because rare-earth phosphors are considerably more expensive, longer length and larger diameter lamps commonly coat the bulb walls with two phosphor layers: a less expensive halophosphor layer and a rare-earth phosphor layer. This maintains the SPD of the rare-earth phosphor while keeping cost relatively low. While some phosphors may be inherently more efficient than others, the most efficient ones cannot always be selected. Since the choice of phosphor or blend of phosphors greatly affects the illumination color of the lamp, a high efficiency phosphor may not have acceptable color properties.

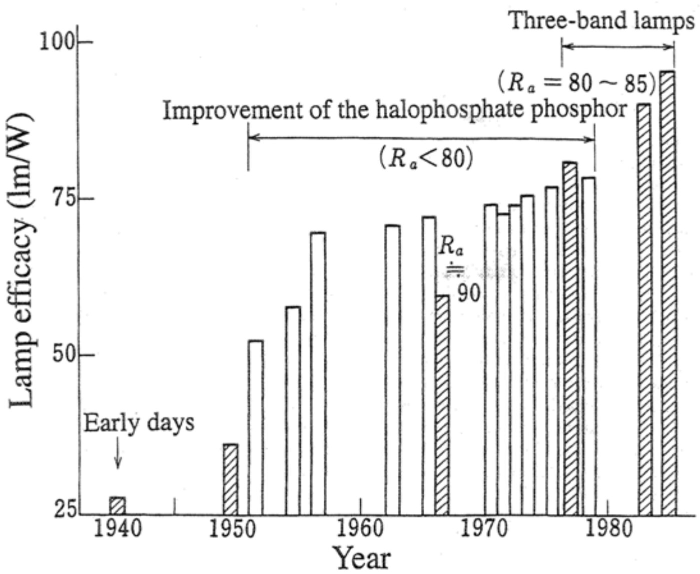


**Figure 3.3.7 Lamp Efficacies for Halo- and Rare-Earth Phosphors**
Source: Phosphor Handbook [19]

DOE has observed that higher-efficiency phosphors on the market typically offer higher CRIs. While CRI is not necessarily positively correlated to efficacy, the majority of phosphors offered in the market currently are. Typically lamps with a CRI in the 60s use only less efficient halophosphors, while lamps with a CRI in the 70s (700-series phosphor) and in the 80s (800-series phosphor) use more efficient rare-earth phosphors.

Apart from the type of phosphor used in a lamp, the thickness of the lamp's phosphor coating also affects lamp efficacy. Generally, as phosphor thickness increases, lamp light output increases until it slightly decreases or stays flat. Figure 3.3.8 illustrates this point, where coating weight is indicative of phosphor thickness.

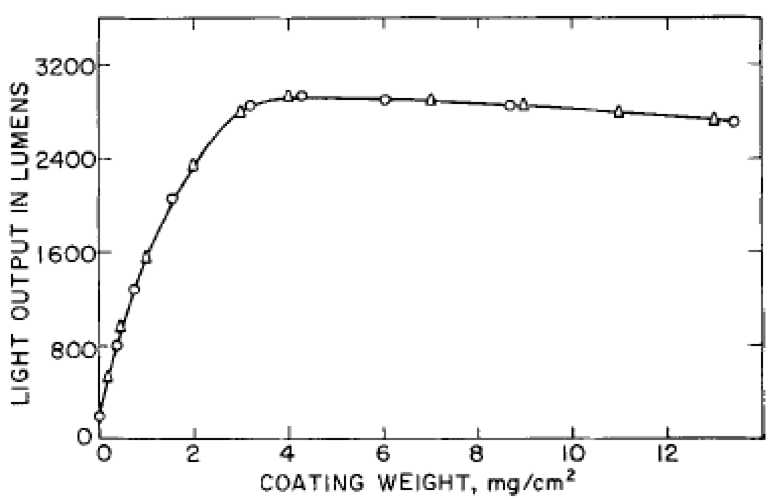


**Figure 3.3.8 Light Output versus Phosphor Thickness**
Source: Journal of the Electrochemical Society [20]

DOE analyzed the rare earth phosphor market to understand the potential impact of the standards on supply and demand, pricing, growth, and the impact on consumers. See appendix 3C for details.

### 3.3.1.4 Glass Coatings

To increase the UV absorption by the phosphors, the bulb glass can be covered with an antireflective coating. This coating is a refractory oxide, such as aluminum oxide ($Al_2O_3$), silicon oxide ($SiO_2$), and titanium oxide ($TiO_2$). This layer is used to reflect any UV radiation that passes through the phosphor back onto the phosphor, allowing a greater portion of UV to be absorbed. As the phosphors absorb more UV radiation, they will emit more visible light, thereby increasing the overall efficacy of the lamp. When these coatings are used with rare-earth phosphors, a good CRI can be achieved while minimizing the phosphor thickness necessary to absorb maximum UV radiation.

### 3.3.1.5 Higher Efficiency Lamp Diameter

Similar to lamp length, lamp diameter is another design parameter of a fluorescent lamp that can affect efficacy. Though both length and diameter often depend on the ballast and fixture in which the lamp is being installed, some manufacturers are trying to allow for variance in the diameter for certain fixtures. As discussed in section 3.4, product classes are not segregated by lamp diameter. Therefore, DOE considers lamp diameter a technology option to increase efficacy.

As Figure 3.3.9 shows, there exists an optimum design diameter for a specific fluorescent lamp type resulting from two opposing effects. First, in small diameter lamps, an increase in diameter decreases the number of electrons and mercury ions that recombine at the bulb wall and produce no light. This lessening of non-radiative recombination results in an increase of optical power output and subsequently a rise in lamp efficacy. However, when the lamp diameter is sufficiently large as to result in minimal non-radiative recombination, a second opposing effect begins to influence the efficacy-diameter relation. With these larger diameter lamps, a further enlargement in diameter causes a greater imprisonment of radiation within the lamp. As the total light output is reduced, the lamp efficacy declines as well. In addition to affecting lamp efficacy, changing the lamp diameter alters the inner surface area of the fluorescent tube. With a larger diameter and therefore surface area, more phosphor is needed to coat the glass, subsequently increasing the cost of the lamp.

DOE only considered lamp diameter as a design option in case of the migration from T12 to T8 lamps. DOE's research indicated T8 lamps are common replacements for T12 lamps, and though the lumen packages for T8 lamps are often less than that of T12 lamps, in this situation, it does not seem to be significant enough to affect consumer utility. Conversely, DOE's research indicated that T5 lamps have more limited utility as replacements for T8 or T12 due to their greater lumen packages. As such, T5 lamps are not considered a design option to improving the efficacy of T8 and T12 lamps.

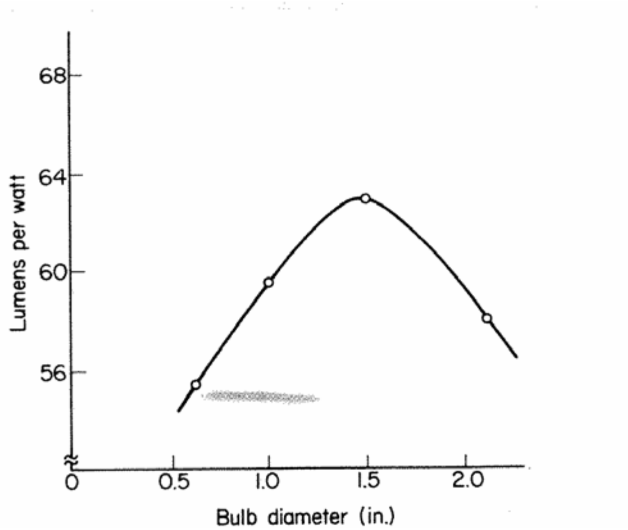


**Figure 3.3.9 Bulb Diameter versus Efficacy**

Source: IESNA Lighting Handbook: Reference & Application[13]

### 3.3.1.6 Multi-Photon Phosphors

The use of multi-photon phosphors, or quantum-splitting phosphors, can significantly improve lamp efficacy. Because these phosphors emit more than one visible photon for each incident ultraviolet photon, a lamp would be able to emit more light for the same amount of power. Development of this technology remains in the research phase.

### 3.3.2 Incandescent Reflector Lamps

An incandescent lamp is a light source in which an electrical current passes through a filament, thermally exiting electrons which then radiate energy in the form of light and heat. Incandescent lamps consist of a bulb, generally composed of glass such as regular lead, soda lime, or borosilicate heat-resisting glass. Sealed to the bulb of the covered GSIL is an E26 medium screw base. Within the bulb, an incandescent lamp contains a filament, filament supports, and sometimes a lamp fill gas. Though early incandescent lamps often used carbon, osmium, and tantalum filaments, current lamps generally use tungsten filaments. Tungsten's low vapor pressure and high melting point allows for high operating temperatures, and consequently high lamp efficacies. The lamp fill gas, though not included in all incandescent lamps, is used to extend the lifetime of the lamp.

IRL are incandescent lamps with a reflective coating, most commonly composed of aluminum or silver applied directly to part of the bulb surface. By improving directional lighting, reflector lamps place the same illuminance on a specific area with reduced watts. The most common bulb shapes of reflector lamps are R, PAR, BR, and ER. R-shaped lamps are primarily for indoor applications, while PAR lamps are usually used outdoors. IRL can be spot floods or floods. Flood IRL, which provide a greater distribution of light, typically have a beam spread of 16 to 40 degrees. Spot IRL have a beam spread from 9 to 16 degrees.

The following assessment is a discussion of technology options to improve the efficacy of IRL. In discussing methods to affect the efficacy of an incandescent lamp, it is important to recognize the interrelation of a lamp's wattage, luminous output, and lifetime. Often the most efficacious incandescent lamps have very low lifetimes and therefore become useless to the consumer. An indirect method to increase overall efficacy involves increasing lifetime. With a longer lifetime, a more efficacious lamp can be manufactured and will still have utility to the consumer.

### 3.3.2.1 Higher Temperature Operation

In the operation of an incandescent lamp, a current is passed through a tungsten filament, which when heated, emits light. However, an incandescent light source's spectrum does not fall exclusively in the visible region of the electromagnetic spectrum, shown in Figure 3.3.10. By operating the filament at higher temperatures, the spectral output shifts to shorter wavelengths, increasing its overlap with the photopic spectral eye sensitivity. This, in effect, increases the luminous output for a given power input and consequently increases the lamp efficacy. As Figure 3.3.11 shows, increasing color temperature (a direct effect of, but not equivalent to, raising operating temperature) causes an increase in luminous efficacy. One way to increase the filament temperature is by increasing the wattage of the lamp. As a higher current passes through and a high voltage drop occurs over the filament, the amount of energy released in the form of heat increases, thereby raising the temperature. However, this significantly changes the luminous output of the lamp and may not meet the consumer's needs. Other technologies that address a lamp's ability to operate at high temperatures are filament thickness, inclusion of inert gas fills, and the use of halogen fills, all discussed below.

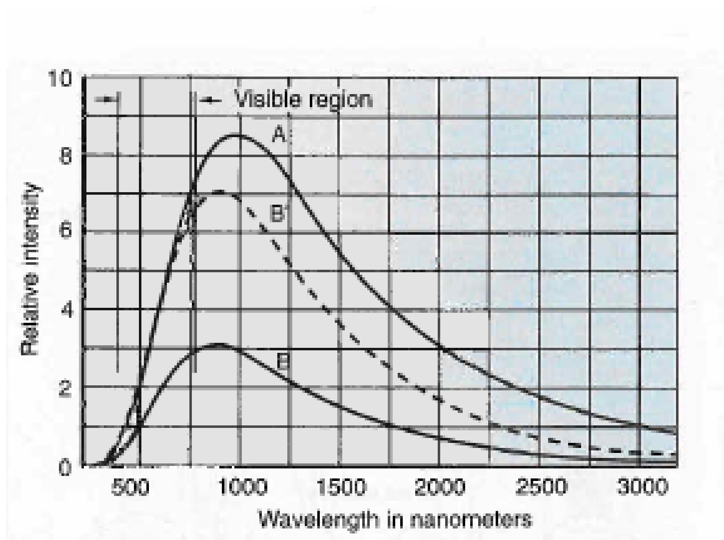


**Figure 3.3.10 Radiating Characteristics of Tungsten**
Source: IESNA Lighting Handbook: Reference & Application [21]

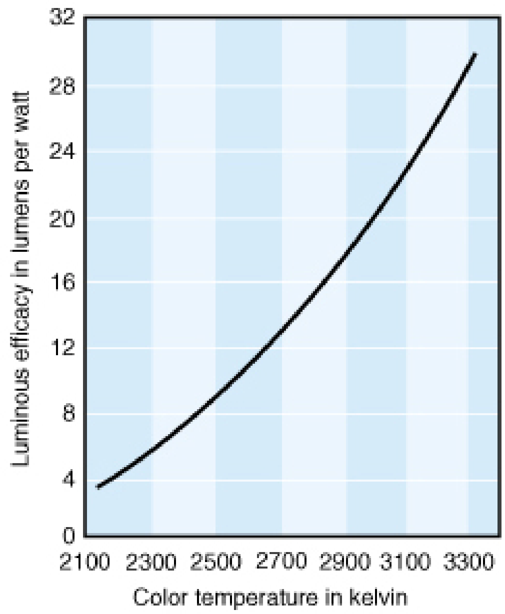


**Figure 3.3.11 Luminous Efficacy versus Color Temperature**
Source: IESNA Lighting Handbook: Reference & Application [22]

In addition to efficacy, the change in operating temperature also affects lifetime and the color appearance of the lamp. At the melting temperature of tungsten, 6,120°F, the maximum efficacy of an incandescent lamp with an uncoiled tungsten filament is 53 lm/W. However, to obtain long life in an incandescent lamp, the filament should be significantly below its melting point. As the filament burns hotter, more tungsten evaporates from the filament. When the filament eventually breaks, the lamp fails. This is an example of the clear tradeoff between lamp efficacy and lamp lifetime. Also, to maintain the cool bulb surface, high temperature incandescent lamps often require larger bulbs. This affects the fixtures in which they fit.

#### 3.3.2.2 Microcavity Filaments

Texturing of the filament surface can increase surface area and therefore emissivity. Filament surface perforations also can act as waveguides for visible light. One technology includes the creation of microcavity holes in the filament surface. The cavities may then be filled with materials such as tantalum, rhenium, molybdenum, tungsten, SiC, rare-earth elements, glass beads, or any combination thereof. Depending on their fabrication, this technology can result in a variety of effects such as greater control of emissive direction, reduction of infrared radiation, and increased emission efficiency over a certain bandwidth of wavelengths. Ultimately, these effects produce a higher overall efficacy.

Sandia National Laboratories researchers examined microcavity resonance in a tungsten photonic lattice. DOE has found multiple patents referencing this technology. However, research indicates that materials patterned at the submicron level may experience problems with stability.[23]

### 3.3.2.3 Novel Filament Materials

In choosing a filament, some advantageous properties are high melting point, low vapor pressure, high strength, high ductility, and good radiating characteristics. While tungsten is primarily used for incandescent lamps, manufacturers also incorporate other metals such as rhenium to improve ductility. However, these lamps are most commonly used for applications requiring vibration-resistant lamps. Novel filament materials such as nitrides and carbides have the potential to improve lamp efficacy by emitting more light in the visible spectrum at a given temperature than traditional tungsten filaments. However, these novel filaments can also be brittle, an attribute that can shorten the lamp lifetime.

### 3.3.2.4 Thinner Filaments

A thinner filament has an increased resistance and therefore an increased operating temperature. As previously discussed, a higher operating temperature results in a higher lamp efficacy. However, as an adverse effect, an incandescent lamp with a thinner filament cannot withstand as much tungsten evaporation before failing, resulting in a shorter lifetime.

### 3.3.2.5 Efficient Filament Coiling

Coiling of the incandescent lamp filament can increase luminous efficacy. The light output of an incandescent lamp is directly proportional to the light-emitting surface area of the light source. By coiling the filament, a longer filament can be used, increasing luminous output and therefore lamp efficacy. Coiling of the tungsten also affects the heat loss from the filament. The more the filament is coiled, the less the effective area for convective cooling, thereby increasing filament temperature and lamp efficacy. IRL covered in this rulemaking generally contain filaments of the type C (coiled) or CC (coiled coil). The highly efficacious CC type filament, which is more commonly used, consists of the coil wound into another helical coil.

### 3.3.2.6 Crystallite Filament Coatings

A variety of filament coatings may be used to increase the efficacy of incandescent lamps. Layers of micron or submicron crystallites, comprised of thorium, tantalum, and/or niobium, are deposited on the filament surface. The crystallites are coated with a protective layer of at least one oxide of thorium, hafnium, scandium, yttrium, cerium, or zirconium. This coating increases the emissivity of the filament in the visible part of the spectrum without increasing the infrared radiation. However, as the operating temperature of the filament increases, the emissivity improvement due to the crystallites decreases.

### 3.3.2.7 Efficient Filament Orientation

Tungsten filament in incandescent lamps can be positioned horizontally or vertically with respect to the base of the bulb. Because the light emitted from the filament is distributed in all directions, one way to improve efficacy is by designing the lamp in a way such that the most amount light is able to escape the bulb. By positioning the filament in a horizontal orientation, the base of the lamp absorbs much of the emitted light along the length of the coil. However, by positioning the filament in vertical alignment, only a small portion of the light is emitted towards the base.  Consequently, more light escapes the bulb and is used for illumination.  This can increase the efficacy of an incandescent lamp by approximately 8 percent.

#### 3.3.2.8 Higher Efficiency Inert Fill Gas

IRL covered in this rulemaking typically are filled with an inert fill gas whose primary purpose is to reduce the evaporation of tungsten, preventing bulb blackening and increasing lifetime.  In addition, this fill gas increases the pressure inside the bulb or halogen capsule. However, the fill gas also provides a means of convective heat transfer between the heated filament and cool bulb surface.  This cooling of the filament represents a power loss and an efficacy reduction due to low temperature operation.  Krypton's low thermal conductivity decreases the convective cooling of the filament, allowing for higher temperature operation and therefore higher efficacy.  In addition, since the krypton molecule is larger than other elements such as argon, krypton more effectively slows the evaporation of the filament and therefore extends the life of the lamp.  Xenon, having even lower heat conductivity and larger mass than krypton, can more drastically change efficacy and life but also at a greater cost.

DOE analyzed the potential impact of standards on xenon availability and pricing in appendix 3B.

#### 3.3.2.9 Luminescent Gas

A large portion of the incandescent spectrum is composed of wavelengths that cannot be detected by the human eye.  By reacting with these wavelengths, luminescent gases can convert some portion of the "invisible" part of the incandescent spectrum into visible light. This conversion increases the amount of lumens emitted by the lamp and thus improves its efficacy.

#### 3.3.2.10 Tungsten-Halogen Lamps

Tungsten-halogen lamps are a subgroup of incandescent lamps which use a halogen element such as bromine, chlorine, fluorine, or iodine to help increase lifetime of the lamp. As discussed earlier, technologies that increase lifetime also indirectly improve efficacy, because higher temperature operation becomes more feasible while maintaining product utility.  In a tungsten-halogen lamp, a small diameter fused quartz envelope filled with a halogen molecule surrounds the filament.  Above 500 degrees Fahrenheit, when tungsten evaporates from the filament, the tungsten molecules combine with the halogen into a gaseous compound.  This compound circulates within the envelope until it contacts the filament again.  The heat of the filament breaks the compound, freeing the halogen and re-depositing the tungsten on the filament.  This regenerative process greatly extends the life of incandescent lamps by reducing the loss of tungsten material.  Also, because tungsten is not being deposited on the bulb surface, bulb darkening over time is greatly reduced.  However, to prevent this bulb darkening, the halogen lamp must be operated with a sufficiently high bulb wall temperature.  For this reason, dimming circuits that employ low-voltage operation may not reap the same benefits from using tungsten-halogen lamps.  One drawback to the halogen technology is that the halogen capsule is often under high pressure and therefore susceptible to exploding.  For this reason, halogen IRL often employ a thicker protective glass.

#### 3.3.2.11 Higher Pressure Tungsten-Halogen Lamps

Increasing the pressure of the halogen capsule by increasing the density of halogen elements can indirectly raise the efficacy of the tungsten-halogen lamp. The increased density of halogen elements raises the probability that an evaporated tungsten element combines with a halogen element in a gaseous compound. Adding more of this gaseous compound in the capsule effectively increases the amount of tungsten re-deposited on the tungsten filament, which can lengthen the lifetime of the tungsten-halogen lamp or raise its efficacy by allowing for higher temperature operation of the filament.

#### 3.3.2.12 Non-Tungsten-Halogen Regenerative Cycles

The regenerative cycle of filament evaporation and re-deposition can be used to greatly increase the life of an incandescent lamp. The filament can burn at a higher temperature than conventional incandescent lamps while maintaining a useful service life. The tungsten-halogen regenerative cycle is the most common. However, other regenerative cycles are possible. Implementation of a non-tungsten-halogen regenerative cycle depends on incorporating a non-tungsten filament.

#### 3.3.2.13 Infrared Glass Coatings

Infrared coatings on incandescent lamps are used to reflect some of the radiant energy emitted back onto the filament. This infrared radiation then supplies heat to the filament and the operating temperature increases. As discussed earlier, an increase in operating temperature results in a higher light output and therefore an increase in efficacy. In addition, the spectrum of the incandescent lamp shifts toward shorter wavelengths. These infrared coatings can be in many forms, such as multilayer dichroic filters and crystal lattice structures whose spacing defines a photonic bandgap. They can be applied to the glass halogen capsule for tungsten-halogen lamps. However, they are most commonly used in the coating of the halogen capsule since one can achieve the greatest directed reflection back onto the filament for the lowest infrared coating usage. Because the halogen capsule is most traditionally in a cylindrical shape, when infrared coatings are applied to a halogen lamp, manufacturers use a cylindrical capsule to help direct the light. Appendix 5D discusses IR coatings in greater detail.

#### 3.3.2.14 Infrared Phosphor Glass Coating

Salts of the rare earths and other transition group elements contain ions at energy levels that are particularly suited to emit visible light when in transition[24]. In the presence of infrared light, these ions will jump to higher energy levels. In some cases, when the ions fall to lower energy levels, light in the visible spectrum is emitted. When used as a coating on a bulb surface, infrared phosphors are able to harvest the emitted infrared energy and convert it to visible light, potentially increasing lamp efficacy.

#### 3.3.2.15 Integrally Ballasted Low-Voltage Lamps

The filaments of incandescent lamps designed to operate at a low voltages are both shorter in length and thicker in diameter than the filaments of incandescent lamps designed to operate at a higher line voltage. Increasing the thickness of the filament can improve lamp efficacy by increasing the filament temperatures. Using an integral ballast allows an increase in the efficacy of a lamp because it operates at low voltages, though it is used in a socket with main line voltage (i.e., it converts the operating voltage of the lamp to a lower wattage from line voltage). The conversion of line voltage to lower lamp operating voltages has associated energy losses. However, modern integral ballast technologies allow efficacy gains from low-voltage operation to outweigh any such conversion losses.

#### 3.3.2.16 Higher Efficiency Reflector Coatings

Though aluminum is most prevalent as a reflector coating in incandescent reflector lamps, silver coatings can also be applied. While aluminum coatings are applied internally by condensation of vaporized aluminum on the inner surface of the bulb, silver can be applied both on the interior and exterior surfaces of the bulb. When applied externally, the silver coating is protected by a cooper coating and aluminum finish. Silver coatings are generally preferred over aluminum due to their lower light loss. Gold is also extremely reflective and can be used to increase the amount of directed light and therefore efficacy of the lamp. An infrared coating that reflects the infrared radiation back toward the lamp's filament can also be applied. This infrared reflector coating, in the form of multilayer dichroic filters or crystal lattice structures, ultimately increases lamp efficacy by limiting the amount of energy lost through infrared radiation and by increasing lamp operating temperature.

#### 3.3.2.17 Trihedral Corner Reflectors

Due to the shape of many reflector lamps, infrared lens technologies can be incorporated in the cover glass to direct infrared radiation back onto the filament. Conventional infrared coatings on reflector lamps direct the infrared light back into the bulb, but not directly onto the filament. Other parts of the lamp absorb some of this heat, which is therefore a source of energy loss. A trihedral corner reflector is a technology that incorporates individual corner reflectors into the cover glass. These reflectors' shapes provide the unique ability to reflect light directly back in the direction it came. Therefore any light coming from the filament and impinging on the cover glass will be directed straight back to the filament. These reflectors are covered with a dichroic coating, allowing visible light to pass through and escape while causing infrared radiation to reflect back on the filament. As this radiation heats the filament, the lamp requires less input power to operate at a higher operating temperature, and therefore operates more efficaciously.

#### 3.3.2.18 Efficient Filament Placement

Placement of the filament is an important aspect of incandescent reflector design. The placement of the filament is optimal when a portion of the spectrum emitted by the filament is focused back onto the filament. This additional radiation supplies heat to the filament and the operating temperature increases. As discussed earlier, an increase in operating temperature results in a higher light output and therefore an increase in efficacy.

## 3.4 PRODUCT CLASSES

When evaluating and establishing energy conservation standards, DOE divides covered products into classes by the type of energy used, capacity, or other performance-related features that affect efficiency, and factors such as the utility of the product to users. (See 42 U.S.C.

6295(q)) DOE usually establishes different energy conservation standards for different product classes. DOE applied the criteria of 42 U.S.C. 6295(q) to GSFL and IRL to develop product classes for the final rule. This section of the TSD describes the product classes DOE has considered for this rulemaking.

### 3.4.1 General Service Fluorescent Lamps

In setting energy conservation standards for fluorescent lamps, EPCA established product classes based on its definition for fluorescent lamps and on nominal lamp wattages. Table 3.12 shows the product classes set by EPCA—two for each lamp type—for a total of eight product classes. (42 U.S.C. 6295(i)(1)(B))

**Table 3.12 EPCA Product Classes for General Service Fluorescent Lamps**

| Product Class | Lamp Type | Nominal Lamp Wattage |
|---|---|---|
| #1 | Four-Foot Medium Bipin | > 35 W |
| #2 | Four-Foot Medium Bipin | ≤ 35 W |
| #3 | Two-Foot U-Shaped | > 35 W |
| #4 | Two-Foot U-Shaped | ≤ 35 W |
| #5 | Eight-Foot Single Pin Slimline | > 65 W |
| #6 | Eight-Foot Single Pin Slimline | ≤ 65 W |
| #7 | Eight-Foot Recessed Double Contact High Output | > 100 W |
| #8 | Eight-Foot Recessed Double Contact High Output | ≤ 100 W |

The fluorescent lamp market has changed in the 17 years since amendments to EPCA established these eight product classes. For example, new phosphors are used more frequently in general illumination applications, changing average CRI values, and new lamps have entered the market, shifting the market share to different lamp wattages. DOE has revised the product classes to reflect some of these market changes, and to enable the analysis to better represent the current market. DOE also reviewed the existing product classes to ensure that any additional GSFL it regulates fit within the same regulatory framework as existing standards. In its assessment of GSFL product classes, DOE looked to statutory criteria (42 U.S.C. 6295(q)) and identified utility and physical attributes of fluorescent lamps around which to set product classes.

In the final rule Federal Register notice, DOE sets product classes on the following utility and physical attributes of fluorescent lamps: physical constraints of lamps (i.e., lamp shape and lamp length), lumen package (i.e., regular versus HO), and correlated color temperature.[i] DOE chose not to set product classes based on lamp wattage, lamp diameter (i.e., T8 vs. T12), or CRI. In addition, DOE did not consider interoperability of lamps on the same ballast system as a

[i] In the Framework Document, DOE presented its preliminary thoughts on revising the table of standards established by EPCA. ((42 U.S.C. 6295(i)(1)(A); see 10 CFR 430.32(n)(1)). DOE considered subdividing the product categories by introducing lamp tube diameter as a differentiating variable (i.e., ">T8" and "≤T8"). In presenting this concept, DOE used the same wattage divisions and minimum CRI requirements that EPCA uses for these lamps, with T8 and T12 lamps in the same product class. Having conducted additional research on the GSFL market and GSFL technologies, DOE does not believe separating product classes by lamp diameter is necessary.

differentiating factor for product classes. The following subsections discuss these lamp attributes and how they pertain to product class divisions.

#### 3.4.1.1 Physical Constraints of Fluorescent Lamps

The physical constraints of the lamp relate to its shape and length. Because consumers must change a lamp fixture to substitute lamps of different geometries for one another, lamp shape affects utility. For example, a U-shaped lamp could not substitute for a linear-shaped lamp in the same fixture. Similarly, given their metric lengths, T5 lamps cannot be used as direct replacements for T8 or T12 lamps in some applications. These lamps may require different lamp holders (due to differences in length and base type). Also, a 4-foot lamp may have a different utility than an 8-foot lamp, as these lamps generally require different fixtures. In addition, a lamp's geometry also affects its efficacy. For example, efficacy tends to increase with length. All else being equal, 8-foot lamps generally have higher efficacy values than 4-foot lamps. Also, a 2-foot U-shaped lamp, while having the same overall tube length, is less efficacious than a 4-foot linear lamp, partly because the electrical arc within the tube has to bend to conform to the lamp shape. Given the impact that geometry has on both utility and efficacy, DOE maintains the division of product classes by lamp geometry.

#### 3.4.1.2 Lumen Package

Lumen package refers to the quantity of light that a lamp-and-ballast system provides to a consumer. To obtain a high lumen package, certain lamps are designed to operate with ballasts that run the lamps at high currents. For example, 8-foot RDC HO lamps and 4-foot MiniBP HO lamps tend to operate at higher currents than 8-foot SP slimline lamps and 4-foot MiniBP SO, respectively. This difference in operating design increases the quantity of light per unit lamp length.

DOE observed that consumers tend to use systems with different lumen packages for different applications. For example, high-lumen-output systems may be installed in certain high-ceiling or outdoor applications, where large quantities of light are needed. Alternatively, standard-lumen-output systems might be installed in lower-ceiling applications such as offices or hospitals, where, for example, distance between the light source and the illuminated surfaces is not as large. Notable differences in the application of SO versus HO lamps indicate a difference in utility.

In addition to producing higher light output, operating lamps at a higher current also decreases efficacy. For example, the efficacy of an 8-foot RDC HO lamp is as much as 10 percent lower than that of a comparable 8-foot SP slimline lamp. Given the observed utility distinctions and notable efficacy differences between SO and HO lamps, DOE maintains the product class division for 8-foot linear lamps between slimline and HO lamps.

In addition, a lamp's lumen package provides a unique utility in the form of a quantity of light per unit lamp length. Because 4-foot T5 MiniBP lamps have similar total lumen output as 4- foot T8 and T12 MBP lamps over a significantly smaller surface area, T5 lamps are often marketed as too bright for use in direct lighting fixtures. If 4-foot T5 MiniBP lamps were regulated in the same product class as 4-foot MBP lamps, the standard could effectively mandate the use of T5 lamps. To prevent eliminating lamps appropriate for direct lighting applications, DOE believes that 4-foot MiniBP lamps (T5 lamps) warrant a separate product class from 4-foot MPB lamps (primarily T8 and T12 lamps).

### 3.4.1.3 Correlated Color Temperature

As discussed in section 3.3.1.3, in general terms, the CCT is a measure of the perceived color of the white light emitted from the lamp. As the spectral emission from the lamp is modified to change the CCT, the lamp efficacy can vary. Due to their greater blue light content, higher CCT fluorescent lamps tend to have lower efficacies.

For fluorescent lamps, the differences in CCT of the light emission can be so large that they affect the efficacy of the lamp. Given the impact on efficacy of CCT and utility, DOE is establishing product classes by CCT range and setting separate efficacy requirements for GSFL based on CCT. DOE is considering establishing two groups that divide the span of CCT that are considered general purpose (between 2,500K and 7,000K). This division of product classes occurs at 4,500K.

### 3.4.1.4 Ballast Interoperability

Not all lamps operate on the same ballast. Even if lamps have similar geometries, different ballasts may be required for their operation. However, DOE treats ballast interoperability as an economic issue (in the LCC and NIA analyses) rather than a product class issue. In other words, if a consumer needs to change the ballast to replace a lamp, then the installed cost of both the lamp and ballast are factored into the net present value equation. For example, DOE considered a T8 lamp a more efficacious replacement for a T12 baseline lamp. Considering T8 lamps as substitutes for T12 lamps is consistent with DOE's understanding of the market, and with manufacturer marketing literature. It is common practice, for example, to replace a T12 lamp-and-ballast system with a T8 lamp-and-ballast system. In its economic analysis, DOE accounts for the need to install a new ballast to operate the T8 lamp by including the installed cost of a new lamp and ballast for the T8 replacement. Had DOE elected to differentiate these lamps on ballast interoperability, or indeed, lamp diameter, this direct comparison may not have been made. DOE believes this approach is appropriate for this rulemaking because there is no unique functionality or service rendered by, for example, one T8 lamp and an equivalent T12 lamp.

### 3.4.1.5 Lamp Wattage

The current regulations group standards by wattage. However, DOE believes that product classes would more appropriately structure standards if they did not divide products by wattage. The main function of a lamp is to provide lumen output, while other attributes such as CCT, for example, contribute to utility. Wattage measures the power consumed by a lamp in providing its service. Therefore, DOE does not construe wattage as a direct measurement of utility. Following guidance from 6295(q), where utility is a factor for structuring product classes, DOE does not establish product classes on the basis of wattage.

Furthermore, DOE believes combining wattages within one product class would allow standards to stay relevant with the market. Dividing product classes by wattage locks the standards to a static wattage structure. While this structure may reflect current product availability, the market may evolve over time, shifting to different wattages. This scenario is illustrated by comparing the current GSFL market to the existing GSFL standard structure. Before the EPCA standard, the 40W GSFL was the most prevalent GSFL offered. Currently, the common wattages for 4-foot MBP GSFL are 40W and 34W for T12 lamps and 32W for 8-foot T8 lamps, where the T8 lamps are energy-saving versions of the T12 lamps.[j] The existing product class divides wattage at 35W.

### 3.4.1.6 Lamp Diameter

As discussed in section 3.3.1.5, lamp diameter is a feature of a lamp which impacts lamp efficacy. In general, DOE considers lamp diameter as a design option, and did not consider using it as a basis for developing product classes.[k] Manufacturer marketing literature and general guidance on lighting design and installation often promote T8 lamp-and-ballast systems as higher efficacy, energy-saving substitutes for T12 lamp-and-ballast systems. Such substitute systems have the same lengths and bases, offer comparable lumen output, and can fit within the same fixtures. Therefore, DOE recognizes that the diameter of the lamp will affect the efficacy, but the utility provided to the end-user is comparable and/or equivalent. The substitution of a T8 lamp for a T12 lamp requires the substitution of a new ballast as well. DOE accounts for new ballast purchases in its economic analyses of these substitutions (i.e., the LCC and NPV analyses) by incorporating ballast costs in the equipment costs of the substitutes.

As stated earlier, DOE generally considers lamp diameter a design option when there is no associated decrease in utility. However, when associated with a decrease in utility, DOE does set separate product classes for different diameter lamps. One such example is for 4-foot T5 MiniBP lamps. In this case, as discussed earlier, DOE establishes separate product classes for 4-foot T5 MiniBP lamps on the basis on the "physical constraints" and "lumen package" class-setting criteria.

### 3.4.1.7 Color Rendering Index

In its standard for fluorescent lamps, EPCA established both an upper and a lower bound on the CRI of GSL.[l] EPCA defines GSFL as having a CRI less than 82, effectively exempting from coverage GSFL with a CRI equal to or greater than 82. (42 U.S.C. 6291(30)(B)(vii); see 10 CFR 430.2) EPCA also established two minimum CRI requirements for each of the four groups of fluorescent lamps, one at 69 CRI and one at 45 CRI. Within 4-foot MBP lamps, for example, EPCA requires that lamps nominally rated at greater than 35W have a minimum CRI of 69 and lamps nominally rated at 35W or lower have a minimum CRI of 45. (42 U.S.C. 6295(i)(1)(A);

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[j] Additional, reduced-wattage T8 4-foot MBP lamps are available, but the 32W version is the most common.

[k] In the Framework Document, DOE considered separating GSFL with diameters smaller than or equal to T8 from lamps with diameters greater than T8. On further consideration, DOE has determined that the lamp diameter does not provide significant unique utility to end-users.

[l] EPCA also defines GSFL as having a CRI less than 82, effectively exempting from coverage GSFL with a CRI equal to or greater than 82. (42 U.S.C. 6291(30)(B)(vii); see 10 CFR 430.2)

see 10 CFR 430.32(n)(1)) In removing the wattage dividers, DOE is also effectively removing the primary differentiating factor that was used to establish minimum CRI requirements. DOE considers several approaches to resolve this issue in section III.2.a of the NOPR Federal Register notice.

#### 3.4.1.8 Product Classes and Standard Form for GSFL

For all the reasons discussed above, DOE is considering the GSFL product classes listed in Table 3.13. DOE is setting constant efficacy level standards by product class, consistent with existing standards. This standard would apply to and be constant over the full spectrum of wattages and diameters for lamps covered by that lamp type and CCT. Chapter 5 provides detail on the selection of trial standard levels.

**Table 3.13 DOE NOPR Product Classes for GSFL**

| Lamp Type | For CCT ≤ 4,500K, Minimum Lamp Efficacy *lm/W* | For CCT > 4,500K, Minimum Lamp Efficacy *lm/W* |
|---|---|---|
| Four-Foot Medium Bipin | Product Class #1 | Product Class #7 |
| Two-Foot U-Shaped | Product Class #2 | Product Class #8 |
| Eight-Foot Single Pin Slimline | Product Class #3 | Product Class #9 |
| Eight-Foot Recessed Double Contact HO | Product Class #4 | Product Class #10 |
| Four-Foot Miniature Bipin SO | Product Class #5 | Product Class #11 |
| Four-Foot Miniature Bipin HO | Product Class #6 | Product Class #12 |

### 3.4.2 Incandescent Reflector Lamps

In setting energy conservation standards for IRL, EPCA differentiated IRL by wattage and established six nominal wattage ranges or "bins," shown in Table 3.14. (42 U.S.C. 6295(i)(1)(B))

**Table 3.14 EPCA Product Classes for Incandescent Reflector Lamps**

| Product Class | Nominal Lamp Wattage |
|---|---|
| #1 | 40-50 |
| #2 | 51-66 |
| #3 | 67-85 |
| #4 | 86-115 |
| #5 | 116-155 |
| #6 | 156-205 |

#### 3.4.2.1 Wattage

For the same reasons discussed for GSFL (see section 3.4.1.5), DOE is revising the product classes so that they are not structured according to wattage. Instead of a structure that uses wattage divisions, DOE is considering one that encompasses a single range of wattages. DOE believes that wattage is not a direct measure of utility. DOE also believes that a structure that encompasses all wattage could better keep pace with the market should it shift to reduced wattages over time.

As wattage increases for incandescent lamps, efficacy also generally increases. To use a single range of wattages while taking into account variation in efficacy by wattage, DOE is developing a single standard per product class as an equation. This equation sets a minimum efficacy requirement that varies by wattage. Chapter 5 provides more detail on selection of efficacy levels.

#### 3.4.2.2 Modified Spectrum

EISA 2007 adopted a new definition for "colored incandescent lamp"[m] which supersedes DOE's definition previously incorporated at 10 CFR 430.2.[n] This new statutory definition effectively increases the scope of energy conservation standards coverage of IRL to include any IRL that has a lens containing five percent or more neodymium oxide or is a plant light lamp. As both of these types of IRL filter out portions of the emitted spectrum of the lamp, many of these lamps fall under the definition of "modified spectrum" which was also adopted by the new energy legislation. The EISA 2007 definition of "modified spectrum" reads as follows:

"The term 'modified spectrum' means, with respect to an incandescent lamp, an incandescent lamp that—

(i) is not a colored incandescent lamp; and

(ii) when operated at the rated voltage and wattage of the incandescent lamp—

I. has a color point with (x,y) chromaticity coordinates on the Commission Internationale de l'Eclairage (C.I.E.) 1931 chromaticity diagram that lies below the black-body locus; and

II. has a color point (x,y) chromaticity coordinates on the C.I.E. 1931 chromaticity diagram that lies at least 4 MacAdam steps (as reference in IESNA LM16) distant from the color point of a clear lamp with the same filament and bulb shape, operated at the same rated voltage and wattage."

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[m] EISA 2007's definition of "colored incandescent lamp" reads as follows: " The term 'colored incandescent lamp' means an incandescent lamp designated and marketed as a colored lamp that has—(i) a color rendering index of less that 50, as determined according to the test method given in CIE publication 13.3-1995; or (ii) a correlated color temperature of less than 2,500K or greater that 4,600K, where correlated temperature is computed according to the Journal of Optical Society of America, Vol. 58, pages 1528-1595 (1986)."

[n] The definition of "colored incandescent lamp" adopted by the 1997 Lamps Test Procedure Final Rule 62 FR 29221,29228 (May 29, 1997) reads as follows: "*Colored incandescent lamp* means an incandescent lamp designated and marketed as a colored lamp that has a CRI less than 50, as determined according to the method given in CIE Publication 13.2 (see 10 CFR 430.22); has a correlated color temperature less than 2,500K or greater than 4,600K; has a lens containing 5 percent or more neodymium oxide; or contains a filter to suppress yellow and green portions of the spectrum and is specifically designed, designated and marketed as a plant light."

(42 U.S.C. 6291(30)(W))

Modified-spectrum lamps provide unique utility to consumers because they offer a different light output from incandescent lamps, much like fluorescent lamps with different CCT values. The same technologies that modify the spectral emission of a lamp also decrease the lamp's efficacy. To modify the spectrum, the coating absorbs a portion of the light emission from the filament. Neodymium coatings or other coatings on modified-spectrum lamps absorb some of the visible emission from the incandescent filament (usually red), creating a modified, reduced spectral emission. Since the neodymium or other coatings absorb some of the lumen output from the filament, these coatings decrease the efficacy of the lamp.

DOE is concerned that, given the newly adopted definition of "colored incandescent lamp," if DOE were to subject modified-spectrum IRL to the same standard as standard-spectrum IRL, then these IRL with modified-spectrum glass or coatings may not be able to achieve the mandatory standard. Therefore, DOE is planning to establish separate product classes for standard-spectrum IRL (those without modification to the spectral emission) and modified-spectrum IRL (some portion of the spectral emission is absorbed). However, to ensure that a suitable standard level is set for these lamps, such that they are neither disadvantaged nor advantaged compared to standard-spectrum lamps, DOE is then establishing an appropriately scaled efficacy requirement based on DOE's analysis of standard-spectrum IRL. This requirement would be adjusted to account for the portions of the spectrum that are absorbed by the neodymium or spectrally enhancing coating. DOE discusses how this scaling would be accomplished in chapter 5 (the Engineering Analysis).

#### 3.4.2.3 Lamp Diameter

IRL diameter provides a distinct utility to the consumer such as the ability of reduced diameter lamps to be installed in smaller fixtures. In addition, efficacy declines with a smaller lamp diameter for a variety of reasons. A smaller diameter lamp has an inherently lower optical efficiency than a larger diameter lamp given a similar filament size. Furthermore, manufacturing PAR20 lamps such that they could be compliant with efficacy standards would be very difficult since technology options available to larger lamps are not necessarily applicable to PAR20 lamps. Therefore, DOE is proposing to establish separate product classes for lamps with a diameter of 2.5 inches or less and lamps with a diameter greater than 2.5 inches.

#### 3.4.2.4 Rated Voltage

A sizable portion of standard halogen product sales consists of lamps with a rated voltage of 130V. However, DOE's research indicates that customers almost always operate these 130V lamps at 120V (normal line voltage), which doubles their lifetime but reduces their efficacy below standard levels. When operated under 120V conditions, lamps rated at 130V in compliance with existing IRL efficacy standards are generally less efficacious than lamps using equivalent technology rated at 120V. Because of this inherent difference in efficacy, it may be less costly to manufacture a lamp rated at 130V and tested at 130V that complies with a standard than a similar 120V lamp complying with the same standard. For example, if DOE were to adopt a minimum efficacy requirement that would effectively require HIR technology for 120V lamps, due to differences in the test procedures for lamps rated at 130V, a 130V lamp may only need to employ an improved halogen technology, which would be less costly. If DOE does not establish a separate standard for lamps rated at 130V, more consumers may purchase 130V lamps because they are less expensive. When consumers operate these lamps at 120V, in order to obtain sufficient light output, they may use more energy than standards-compliant 120V lamps. This practice would increase energy consumption and result in lamps operating with a lower efficacy than any cost-justified standard level. Therefore, to preserve the energy savings intended by these standards, DOE establishes two separate product classes: (1) lamps with a rated voltage less than 125V, and (2) lamps with a rated voltage greater than or equal to 125V.

#### 3.4.2.5 Spot Versus Flood Incandescent Reflector Lamps

In the Framework Document, DOE considered setting product classes for IRL based on beam spread. In particular, DOE considered separate standards for spot and flood IRL. DOE reviewed technical reports on the performance of spot and flood reflector lamps. DOE concluded that while there might be different utility for consumers through the light distribution patterns of a spot reflector lamp versus a flood reflector lamp, the difference in utility does not affect the efficacy of the lamp. Thus, DOE will not create separate product classes for spot and flood reflector lamps.

#### 3.4.2.6 Product Classes and Standard Form for IRL

In sum, DOE is considering all wattages of IRL to be part of the same product class, allowing for the standard to be a function of the lamp wattage. As DOE considers more efficacious replacement lamps, the rated wattages must decrease to maintain consistent levels of light output and save energy. In addition, DOE is considering energy conservation standards for full-spectrum IRL separately from modified-spectrum IRL and also makes distinctions based on lamp diameter and rated voltage. Table 3.15 summarizes the eight product classes DOE considers for the NOPR. To facilitate stakeholder comment on the IRL product classes, DOE has continued the product class numbering from the GSFL.

**Table 3.15 DOE NOPR Product Classes for IRL**

| Diameter | Voltage | Standard-Spectrum Minimum Lamp Efficacy *lm/W* | Modified-Spectrum Minimum Lamp Efficacy *lm/W* |
|---|---|---|---|
| > 2.5 Inches | ≥ 125V | Product Class #13 | Product Class #17 |
| | < 125V | Product Class #14 | Product Class #18 |
| ≤ 2.5 Inches | ≥ 125V | Product Class #15 | Product Class #19 |
| | < 125V | Product Class #16 | Product Class #20 |

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